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Determination of deep levels' parameters in epi-GaAs by a transient acoustoelectric technique

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Abstract. A new acoustoelectric method is developed in order to study solid state layered structures. The method is based on the transient transverse acoustoelectric voltage (TAV) measurements. The decay of the TAV signal is read when a surface acoustic wave (SAW) producing the signal is switched off. The shape of the transient voltage and its spectral dependence on the wavelength of a light irradiation are studied. A theoretical model is presented to explain the transient TAV data. The results demonstrate that the transient acoustoelectric technique is an effective means of characterizing trapping centres in the bulk and at surfaces or interfaces of epitaxial semiconductor structures.

1. Introduction

In recent years, numerous methods have been used to study lattice defects in solids and deep levels in semiconductors. Most of them, for example the modern scanning tunnelling microscopy technique, allow one to characterize surface defects. However, taking into account that the size of layered structures is remarkably small, reliable experimental techniques for characterization of interface defects are still lacking. For example, applications of positron annihilation techniques frequently used in these studies are rather limited because the interface area is small. Also, the quality and performance of multilayered and epitaxial semiconductor structures are known to be strongly affected by defects [1–3] located at the interfaces between epilayers and substrates. Very recently, some data indicating that lattice defects influence the transient acoustoelectrical effect in semiconductors became available [4–6]. Among other experimental techniques utilizing the acoustoelectric effect, measurement of the transient transverse acoustoelectric voltage (TAV) generated in semiconductors has been used in the past [7–10]. Nowadays, the acoustoelectric voltages in modern low-dimensional and nanostructured materials are also being investigated [11–13].

Our aims in this work are (i) to study parameters of the transient TAV signal under well defined experimental conditions and (ii) to characterize the deep trapping levels in epilayered GaAs by the transient TAV technique. We present both the theoretical and experimental results on complex transient TAV measurements and show that this technique allows one to characterize defect states in epitaxial semiconductor structures.

The transverse acoustoelectric voltage is produced by ultrasonically activated redistribution of electrical charges in semiconductors. It is generated across layered systems which consist of piezoelectric and semiconducting materials due to piezoelectric fields of the surface acoustic wave (SAW) propagating along the piezoelectric plate. The SAW is excited by an rf voltage V_p applied to a transducer deposited onto the surface of the piezoelectric plate. Usually, a $LiNbO_3$ plate is used as a SAW waveguide. A simplified experimental arrangement is shown in figure 1(a). Semiconductor structures with remarkably low dimensions and with both piezoelectric and nonpiezoelectric layers can be studied by using this set-up. If the semiconductor itself exhibits piezoelectric behaviour, one can directly excite the SAW in this sample by depositing an interdigital transducer on its surface using the arrangement sketched in figure 1(b). In both cases, piezoelectric fields of the SAW penetrate inside the semiconductor, causing a redistribution of charge carriers in the near-surface region.

Two main mechanisms explaining the TAV effect are known in semiconductors. The first one, the so-called concentration effect, is due to the variable component of the sample's conductivity σ_v [14]. It occurs as a result of a redistribution of the electron concentration in the variable piezoelectric field E_v of the SAW. Therefore, the direct component of the acoustoelectric current is

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

where an averaging over a period T_A of the SAW is carried out. The relaxation time of this TAV signal component is

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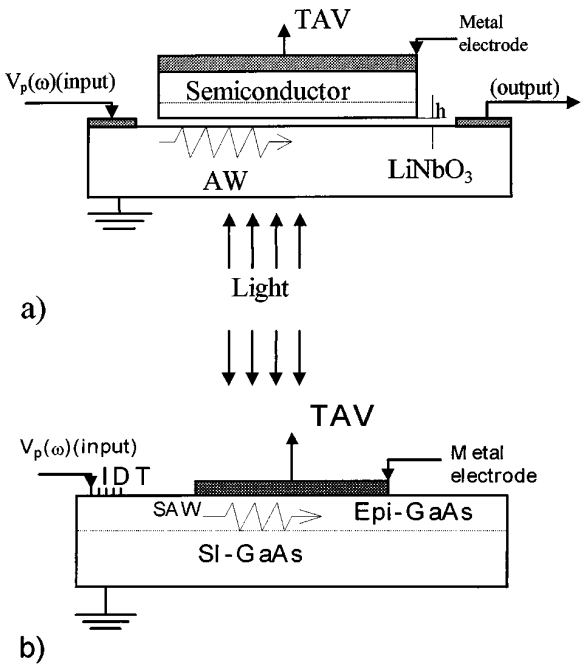

Figure 1. Two versions of sample arrangements for performing transient TAV measurements: (a) separate medium configuration and (b) integrated configuration.

defined by Maxwell's relaxation time τ_m of free charge carriers ($\tau_m = \varepsilon\varepsilon_0/\sigma_0$, σ_0 being the conductivity of a sample). Usually, τ_m is much smaller than the period of the SAW. Therefore, the relaxation time of the 'concentration' TAV can be taken to be zero.

The second mechanism of the TAV is connected with semiconductor defects. The occurrence of high-frequency electrical fields of the SAW in a near-surface region of the sample results in an increase of the concentration of free charge carriers. This, in turn, increases the charge captured in deep trapping levels which are located at the interface or surface. As a result, a direct electrical field perpendicular to the sample surface occurs. The amplitude of this 'trap' TAV component is proportional to the excess concentration of the captured charge [15]. The relaxation time of the appropriate TAV signal is determined by the rate of thermodynamic balance between trap levels and free carriers.

When employing the TAV method, it is necessary to overcome some difficulties in interpretation of experimental results. Thus, the TAV amplitude strongly depends on several parameters and, particularly, the influence of the piezoelectric field E_V on local centres must be taken into account. To avoid these difficulties, we propose to measure the transient TAV signal after the SAW pulse is switched off. Therefore, we can detect a transient part of the TAV signal during the relaxation of the signal to zero level. When working with the SAW pulses, we are primarily interested in the decay time of the TAV amplitude. This transient time is directly related to the rate of certain physical processes occurring in the region spanned by penetrating piezoelectric fields of the SAW. Alternatively, it is possible to use harmonically modulated SAWs. In this case of the so-called frequency regime, we measure the dependence of the TAV signal on the modulation frequency.

2. Theory and data processing

2.1. The transient TAV

For the simplest case of only one type of surface defects, the transient TAV signal can be written as

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

where C_{ae} is some coefficient which depends on the configuration of electrodes and sample parameters. The voltage $V_{ae}(t)$ depends on the relaxation of the nonequilibrium charge $\Delta n_t(t)$ trapped at surface defects. Equation (2) is valid for small deviations from thermodynamic equilibrium, namely when $V_{ae} \ll (kT/e)$, where k is the Boltzmann constant, T is the temperature and e is the electron charge. Therefore, the TAV amplitude should not exceed 25 meV at room temperature. Appropriate displacement of the Fermi level at the surface will be less than kT. It should be emphasized that equation (2) is obviously correct at depleted semiconductor surfaces and in intrinsic semiconductors with a few free carriers. Since the relaxation time does not depend on the particular mechanism of the excitation of an electronic subsystem, it is possible to use the standard theoretical approach with the relaxation time τ as a function of trap level parameters. Restricting our consideration to n-type semiconductors, we thus can write

$$\tau = \frac{1}{N_C V_T S_n}\exp[E_t/(kT)] \tag{3}$$

where N_C is the density of states in the conduction band, V_T is the thermal velocity of free electrons, E_t is the energy depth of the electronic trap level below the edge of the conduction band and S_n is an effective cross section of electron capture by trap centres. Experimentally, it is possible to determine the relaxation time τ by measuring the transient TAV signal. At any temperature T, the values V_T and N_C can be derived from the theory. Then the capture cross section is simply

$$S_n = \frac{1}{V_T N_C \tau}\exp[E_t/(kT)]. \tag{4}$$

To determine S_n from equation (4), it is necessary to know the energy position E_t of the trapping centre. The energy E_t can be found by two methods. Firstly, the semiconductor is illuminated by monochromatic light with different wavelengths. The photon energies $h\nu$ should be smaller than the energy gap E_G, $h\nu < E_G$. By tuning $h\nu$, the peaks in the TAV spectra should arise and they are directly related to the energy depth E_t. An analysis of the spectral behaviour of the TAV signal is given below.

Secondly, it is possible to find E_t by a thermal method. In this case, the temperature of the sample kept in the dark is varied and we can find E_t by taking the TAV relaxation times τ_1 and τ_2 at two respective temperatures, T_1 and T_2,

$$E_t = \frac{kT_2\ln(\tau_1/\tau_2)}{(T_2/T_1) - 1}. \tag{5}$$

Equation (5) is valid if the product $V_T N_C S_n$ is independent of the temperature, which holds for attracting centres. In other cases, it is necessary to take into account the temperature dependence of $V_T N_C S_n$.

2.2. TAV data processing

To proceed further, it is essentially to take into account that usually there exist different types of trap levels and excess concentrations Δn_{ti} of charge carriers captured by the i-type surface traps can be written as

$$\frac{\mathrm{d}\Delta n_{ti}}{\mathrm{d}t} = -\frac{\Delta n_{ti}}{\tau_i} + F_i(t) \tag{6}$$

where τ_i represents the characteristic relaxation time of the i-type level and $F_i(t)$ is an external force which initiates the capture of the excess charge at surface traps. The physical nature of the force is connected with the piezoelectric field of the SAW.

2.2.1. Pulse modulation. When modulating the ultrasonic wave amplitude by rectangular pulses, the external force $F(t)$ has the form

$$F(t) = \begin{cases} \text{constant} & 0 < t < T_p \\ 0 & T_p < t \end{cases} \tag{7}$$

where T_p is the pulse duration. The shape of the transient TAV signal is taken in the region 'BC' of the decay curve presented in figure 2(b). Since the external force $F(t) = 0$ in this region the solution of equation (6) is a decreasing exponential curve with the relaxation time τ_i. In the case of trap levels of different types, the TAV signal can be expressed as

$$V_{ae}(t) = \sum_{i=1}^{N} V_i \exp(-t/\tau_i). \tag{8}$$

The summation in equation (8) is performed over all existing traps in the near surface region with coefficients V_i which are proportional to the concentration of traps of various types. To find V_i, τ_i and N from equation (8), it is necessary to determine the number N of types of participating surface levels. This can be done by analysing the dependences $\ln(V_{ae})$ versus time. Obviously, for $N = 1$, this dependence is a straight line with the slope which gives the relaxation time τ. In the case of two or more exponential components, the plot $\ln(V_{ae})$ versus t has a more complex form. In our experiments, the values V_i and τ_i were determined by interpolating the form of the transient TAV signal (part 'BC' of curve b in figure 2) by a sum of exponential terms.

2.2.2. Harmonic modulation. Now we consider the case of harmonically modulated SAW (figure 2(c)), with

$$F_i(t) = \mathrm{Re}[A_i(1 + m\exp(\mathrm{i}\Omega t))] \tag{9}$$

where A_i are coefficients of proportionality, $\Omega = 2\pi f$ is the modulation frequency and m is the depth of modulation.

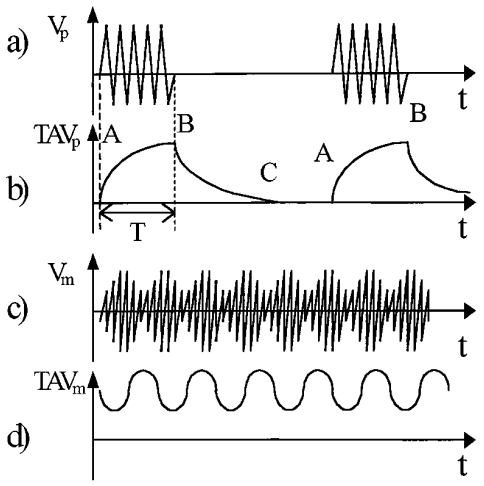

Figure 2. The time course of the input rf voltage V exciting the SAW and the resulting TAV signal in the pulsed ((a) and (b)) and modulation ((c) and (d)) modes.

Taking into account equation (9) and using $t \gg \tau_i$, equation (6) yields

$$\Delta n_{ti} = \mathrm{Re}\left(A_i\tau_i + \frac{A_i\tau_i m}{1 + \mathrm{i}\Omega\tau_i}\exp(\mathrm{i}\Omega t)\right). \tag{10}$$

By assuming an existence of more than one type of surface trap levels, the amplitude $V_{ae}(\Omega)$ of the acoustoelectric signal taken at the modulation frequency Ω can be presented by

$$V_{ae}(\Omega) = \mathrm{Re}\left(\exp(\mathrm{i}\Omega t)\sum_i \frac{V_i}{1 + \mathrm{i}\Omega\tau_i}\right) \tag{11}$$

where the coefficients V_i are independent of Ω. This leads to

$$|V_{ae}(\Omega)| = (V_1^2(\Omega) + V_2^2(\Omega))^{1/2} \tag{12}$$

with the values V_1 and V_2 given by

$$V_1(\Omega) = \sum_{i=1}^{N} \frac{V_i}{[1 + (\Omega\tau_i)^2]^{1/2}}\cos[\arctan(\Omega\tau_i)]$$

$$V_2(\Omega) = \sum_{i=1}^{N} \frac{V_i}{[1 + (\Omega\tau_i)^2]^{1/2}}\sin[\arctan(\Omega\tau_i)]. \tag{13}$$

In our experiments, the frequency dependence $V_{ae}(\Omega)$ has been investigated in order to find characteristic relaxation times τ_i and the experimental plots have then been fitted to equations (12) and (13) with parameters V_i and τ_i. Equations (8), (12) and (13) also include the 'concentration' TAV signal component which one can assume is characterized by $\tau = 0$.

It should be emphasized that equation (8) as well as equations (12) and (13) contain the same information about relaxation times. Whether one uses the time or frequency regime measurements discussed above mainly depend on the available experimental equipment. Furthermore, it should also be pointed out that harmonic modulation allows one to estimate the 'concentration' TAV component which is characterized by $\tau = 0$. In accordance with equations (12) and (13), with increasing frequency Ω,

the 'trap' TAV component tends to zero. However, the 'concentration' TAV component remains constant and does not depend on Ω.

3. TAV measurements

3.1. The experimental set-up and samples

Two types of GaAs layers grown by MOCVD on a 400 μm thick GaAs substrate were investigated. The first type labelled GA-1 was a 0.1–1 μm thick epitaxial layer of n-GaAs whereas the thickness of the layers labelled Ga-2 was close to 8 μm. In both cases, the electron concentrations in the layers were found to be of the order of 10^{14} cm^{-3}. The samples were placed with the epitaxial layer down on a lithium niobate plate which drives the SAW with a frequency of 6 MHz. The TAV signal was picked up between a bottom ground electrode and a flat metal electrode placed on the upper surface of a GaAs sample as shown in figure 1(a). The gap h in figure 1(a) between a lithium niobate plate and a semiconducting sample was about 5 μm. Piezoelectric fields accompanying the SAW penetrate through the air gap into the semiconductor and the field penetration depth is limited to 3–4 Debye lengths. For the GA-1 sample, this roughly gives 0.5–0.7 μm. Therefore, the transient TAV signal was essentially formed in the region of the epitaxial layer. It should be noted that the presented experimental arrangement is very convenient because no special sample preparation procedure is required and sample replacement is easy to do. In particular, it is not necessary to fabricate electrical contacts on the samples.

Since GaAs is a piezoelectric material it can be directly used as a piezoelectric waveguide, as shown in figure 1(b). In this case, SAWs with frequency 67 MHz were excited by means of an interdigital transducer deposited onto the sample's surface. The TAV signal between the ground electrode and an aluminium film which had been evaporated onto the epitaxial layer was then measured. In our measurement, the SAW wavelength was about 30 μm. The penetration depth of the SAW is of the order of its wavelength. However, since the GaAs epilayers were grown on i-GaAs substrates with remarkably low electron concentration the substrate did not considerably influence the resulting TAV signal. Therefore, the filling area of deep trapping levels spanned primarily the epitaxial layer.

It is very important to take an undistorted form of the transient TAV signal. In order to attain such a form, a pre-amplifier with a very high input resistance ($R_{inp} > 10$ GΩ) and small input capacitance ($C_{inp} < 10$ pF) was used. It has been verified that such parameters of the instrument allowed measurements of the true form of the TAV signal's decay. The measurement of the transient TAV can be performed either in the time domain or in the frequency domain. In the pulse mode, the TAV$_p$ pulse exhibits a monotonic increase (AB in figure 2(b)) and a monotonic decrease (BC). This shape of the TAV$_p$ signal is typical for the 'trap' component. In the harmonic modulation mode, the SAW exciting voltage V_m is sinusoidally modulated at a determined frequency, as shown in figure 2(c). In this case, the amplitude of the acoustoelectric voltage TAV$_m$ (figure 2(d)) is detected on the frequency of modulation by means of a selective voltmeter. The TAV relaxation time is then calculated by fitting the frequency-dependent TAV$_m$ plots to equations (12) and (13).

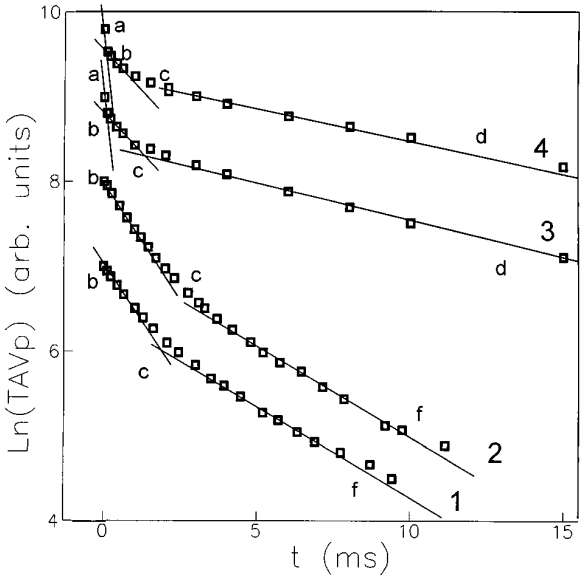

Figure 3. A logarithmic plot of the amplitude of the transient TAV signal versus time. 1 and 2 are plots for GA-1 at exciting rf voltage V_p = 7.8 V (1) and 13.5 V (2). 3 and 4 are plots for GA-2 at exciting rf voltage V_p = 5 V (3) and 10 V (4). Part 'ab' corresponds to the 'concentration' TAV; parts 'bc', 'cd' and 'cf' correspond to three different types of trapping centres.

3.2. Measurements of the transient TAV

For the determination of characteristic relaxation times τ_i of trapping centres and partial amplitudes V_i of the TAV$_p$, the experimental data were processed by the technique described in section 2.2.1. The data obtained with the GA-1 samples reveal the occurrence of two exponential terms with decay times of 2 and 12 ms. Thus, the regions 'bc' and 'cf' in curves 1 and 2 in figure 3 correspond to two types of traps with the relaxation times of 2 and 12 ms, respectively.

The frequency sweep of the TAV$_m$ signal from the sample GA-1 is shown in figure 4, curve 1. Experimental data are presented by dots while the full lines are theoretical calculations which are performed using equations (12) and (13) with two relaxation times $\tau_1 = 2$ and 12 ms. It can be seen that the theory and experiment are in good agreement with respect both to the times τ_i and to the amplitudes V_i. These decay times coincide with those derived from the pulsed TAV$_p$ signals. It can also be seen that the TAV$_m$ amplitude approaches zero at sufficiently high modulation frequencies. Hence, the 'concentration' TAV component can be neglected for the GA-1 sample.

The total TAV$_p$ signal from the GA-2 sample exhibits three different terms denoted 'ab', 'bc' and 'cd' in curves 3 and 4 in figure 3. We can distinguish two types of trapping centres with relaxation times of 4.5 and 22 ms at room temperature. The sign of the TAV$_p$ signal corresponds

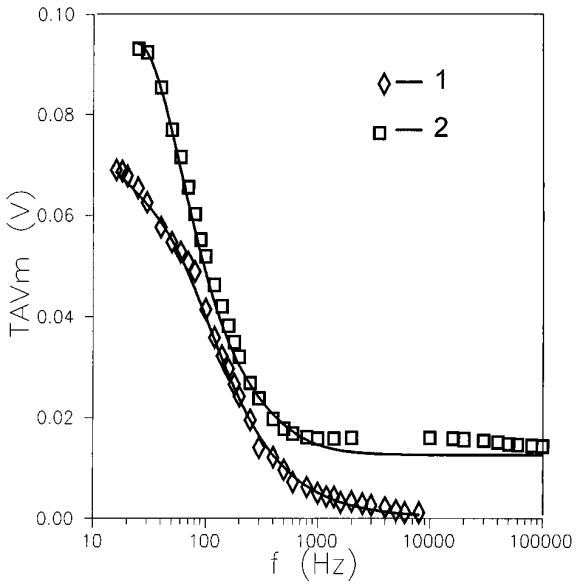

Figure 4. Measured dependences of the TAV_m signal on modulation frequency for the GA-1 and GA-2 sample types. The full lines represent the calculated curves obtained by using equations (12) and (13).

to localization of these traps at the interface between the epitaxial layer and the substrate. The third term contributing to TAV_p is very fast, as can be seen by examining 'ab' regions in figure 3. Accurate estimation of the corresponding relaxation time is somewhat complicated for the pulsed mode because the numerical fitting procedure becomes unstable at $\tau \to 0$. Therefore, we consider the modulation frequency dependence of the TAV_m signal depicted by curve 2 in figure 4. One can see that the TAV_m amplitude decreases with increasing frequency but does not tend to zero, falling down rather to a certain value. This minimum TAV_m signal corresponds to the 'concentration' component of the acoustoelectric voltage. Therefore, the GA-2 sample reveals two mechanisms for formation of the TAV whereas the GA-1 sample is characterized by one mechanism contributing to the TAV signal.

4. Optical spectra of the TAV

The relaxation time τ of the transient TAV is determined by the rate of the thermal emission from and trapping of charge carriers in surface energy levels. In turn, the rate of achievement of the thermodynamic equilibrium between trapping centres and conduction and valence bands in semiconductor structures depends on characteristic parameters of these centres such as the energy depth E_t and effective cross section for electron trapping S_n. The calculation of S_n with equation (4) can be performed if the energy levels E_{ti} are known. For this reason, additional information about E_{ti} is necessary and it can be obtained by measuring optical spectra of the TAV signal.

4.1. Analysis of spectral dependences of the TAV

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 capture of electrons is described by

$$\frac{\mathrm{d}n_t}{\mathrm{d}t} = C_n n_s (N_t - n_t) - \beta_n N_C n_t \tag{14}$$

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 free charge carriers near the surface and C_n and β_n are the probabilities of capture and release of 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:

$$n_t = n_{t0} + \Delta n_t \qquad n_s = n_{s0} + \Delta n_s. \tag{15}$$

In the absence of acoustic waves, the thermodynamic balance is defined by

$$C_n n_{s0}(N_t - n_{t0}) - \beta_n N_C n_{t0} = 0. \tag{16}$$

This equation relates the coefficients C_n and β_n. By substituting equations (15) and (16) into equation (14), one finds

$$\frac{\mathrm{d}\Delta n_t(\lambda)}{\mathrm{d}t} = C_n\{(N_t - n_{t0}(\lambda))\Delta n_s - \{n_{s0}(\lambda) + \Delta n_s(\lambda) + N_C \exp[-E_t/(kT)]\}\Delta n_t(\lambda)\}. \tag{17}$$

Note that Δn_t and Δn_s are averaged over the period of an acoustic wave. The acoustoelectric voltage component is proportional to the excess charge on trap levels ($V_{ae} \propto \Delta n_t$). When measuring the TAV signal and its shape in the pulsed mode under quasi-equilibrium conditions,

$$\frac{\mathrm{d}\Delta n_t}{\mathrm{d}t} = 0 \tag{18}$$

we get from equation (17) the following expression for the 'trap' TAV component:

$$V_{ae} \sim \Delta n_t(\lambda) = (N_t - n_{to}(\lambda)) \times \frac{\Delta n_s(\lambda)}{n_{s0}(\lambda) + \Delta n_s(\lambda) + N_C \exp[-E_t/(kT)]}. \tag{19}$$

The values n_{t0}, Δn_s and n_{s0} vary with the wavelength of light illuminating the sample. However, if the photon energy $h\nu$ does not exceed the energy gap E_G and direct electronic excitation from the valence band to the conduction band does not occur, the changes of the concentrations n_{s0} and Δn_s are rather small. In this case, the TAV spectra are mainly determined by the multiplicand $N_t - n_{t0}(\lambda)$ in equation (19). The TAV signal is formed by electrons captured in the ionized traps which are located above the Fermi level. Since the illumination of the semiconductor's surface is likely to result in partial filling of these trapping centres by electrons from the valence band, the occurrence of an additional charge in the traps provides some displacement of the Fermi level. However, this displacement can be neglected for small TAV amplitudes ($eV_{ae} < kT$). Therefore, the transient TAV technique is applicable for energetic levels located above the equilibrium Fermi level. If the photon energy exceeds the value defined by

$$h\nu = E_G - E_t \tag{20}$$

the charge carriers are transferred from the valence band to capture centres, resulting in a growth of n_{t0}. Then the difference $N_t - n_{t0}(\lambda)$ in equation (20) decreases and a minimum should be observed in the TAV spectrum. When several types of trap levels contribute to the TAV signal, several corresponding minima should be observed in the optical TAV spectrum. In the general case, both electron- and hole-trapping centres are present in a semiconductor. However, in the n-type samples, the concentration of free holes is negligibly small compared with the electron concentration. Therefore, the influence of holes on the TAV signal is insignificant in electronic semiconductors and minima in the TAV spectra are determined by electron trapping centres only.

4.2. Experimental spectra of the transient TAV

For determination of the energy depth of the trapping centre, optical spectra of the transient TAV are investigated. The samples are illuminated with monochromatic light in the energy range 0.6–1.6 eV. Following a mathematical procedure described in section 2.2, the measured TAV signal is divided into partial exponential components with different relaxation times τ_i. Each partial component is characterized by a certain value of partial amplitude V_i which varies with illumination. The amplitudes V_i characterize the contribution of the i-type traps with relaxation times τ_i to the total TAV signal. This contribution attains its minimum value for illumination of the sample surface by monochromatic light with the energy defined by equation (20). Consequently, the spectral position of a minimum in the spectrum of the ith partial amplitude $V_i(h\nu)$ unambiguously determined the appropriate energy level E_{ti}.

The spectra of the partial amplitudes V_i are shown in figure 5. Plot 1 is taken from the GA-1 sample for relaxation times of 12 and 2 ms. The minima in these curves correspond to two types (1* and 3) of deep levels with energy depths $E_1^* = 0.48$ eV and $E_3 = 0.54$ eV below the conduction band which have been calculated by using equation (20). Plot 2 is taken from the GA-2 sample with relaxation times of 22 and 4.5 ms. Using equation (20), we find that the minima in plot 2 correspond to two types (1 and 2) of deep levels with energies $E_1 = 0.48$ eV and $E_2 = 0.20$ eV below the conduction band.

The differences in the relaxation times for the same level $E_t = 0.48$ eV which is found to be 12 ms (plot 1 in figure 5) and 22 ms (plot 2) for the two different samples can be explained as follows. The relaxation time of the captured charge is determined by two parameters–the energy depth E_t of a trapping centre and its capture cross section S_n. The depth depends on the atomic structure of the local defect and hence does not vary from sample to sample. Alternatively, the value S_n depends both on the type of the trapping level and on electrical properties of a semiconductor itself, such as the configuration of the electrical potential near the defect and its shielding by a free charge. Therefore, the characteristic relaxation times for the same trapping levels in various samples can differ.

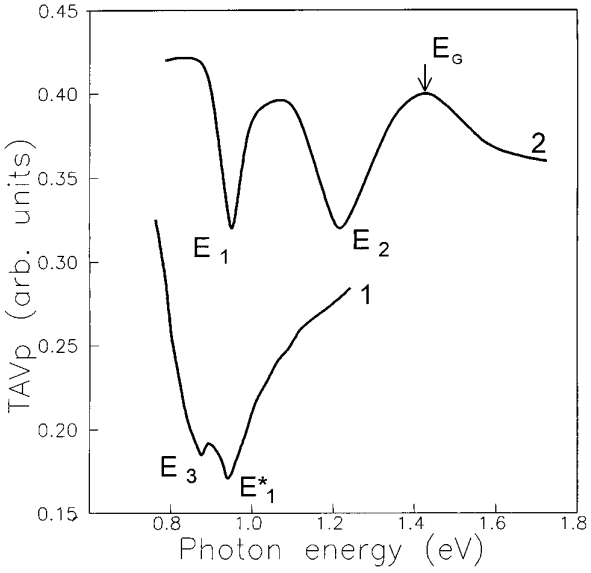

Figure 5. Spectra of the TAV's exponential component: 1, τ = 12 ms (GA-1), τ = 2 ms (GA-1); 2, τ = 22 ms (GA-2) and τ = 4.5 ms (GA-2). Four minima labelled E_1, E_1^*, E_2 and E_3 correspond to the three trapping centres detected in investigated samples. The band gap energy is indicated by E_G.

Table 1. Characteristics of interface trapping centres in MOCVD-grown epi-GaAs at T = 296 K.

Centre	E_t (eV)	τ (ms)	S_n (cm^2)
1	0.48	22 ± 1	2×10^{-15}
1*	0.48	12 ± 1	4×10^{-15}
2	0.20	4.5 ± 0.4	10^{-19}
3	0.54	2 ± 0.3	2.5×10^{-13}

Knowing the energy depths of trapping centres and appropriate relaxation times, we then can calculate the effective cross sections S_n for the capture of charge carriers by these trap centres. The results of the calculations presented in table 1 describe defect parameters in the epitaxial GaAs structures which are studied in this work.

5. Conclusions

Summarizing presented results, we conclude that the transient TAV technique is a reasonably simple and effective method of characterizing the trap centres in epilayer semiconductor structures. The experimental data in conjunction with appropriate mathematical processing allow one to estimate the characteristic relaxation time, energy position in the energy gap and capture cross section for each of these centres.

By investigating MOCVD-grown epitaxial GaAs layers, we found three different types of trapping defects. Their parameters taken at room temperature are summarized in table 1. The relaxation time τ for the E_1 centre is found to be either 12 or 22 ms depending on the type of the epi-GaAs sample. The method described can also be applied

to the investigation of other semiconductor structures, including those based on Si and II–VI compounds.

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