Shallow Levels Characterization in Epitaxial GaAs by Acousto-Optic Reflectance.

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ABSTRACT

Optical spectra of light reflection are detected under an influence of ultrasonic wave (UW) on a GaAs wafer. The differential spectrum is calculated as a difference between those taken under UW and without that influence on a sample. This acousto-optic differential reflectance (AODR) spectrum contains some bands that represent the energetic levels of the shallow centers in a sample. A physical basis of this technique is related to a perturbation of local states by UW. Here, a method is developed for characterization of local states at the surfaces and interfaces in crystals and low-dimensional epitaxial structures based on microelectronics materials. A theoretical model is presented to explain AODR spectra. Also, experiments using epitaxial GaAs structures doped by Te were made. Finally, theoretical and experimental results show that acousto-optic reflectance is an effective tool for characterization of shallow trapping centers in epitaxial semiconductor structures.

RESUMEN

En este trabajo, utilizamos el espectro de la luz reflejada en una muestra de Arsenuro de Galio (GaAs) bajo la influencia de una onda ultrasónica. El diferencial espectral es calculado como una diferencia entre el espectro del material obtenido bajo la influencia del ultrasonido y aquél obtenido sin dicha influencia. Este diferencial de reflectancia espectral acusto-óptico (AODR) contiene algunas bandas que representan los niveles energéticos de los centros en la superficie de la muestra. Esta técnica está basada en la perturbación de los estados locales generada por el ultrasonido. Particularmente, este trabajo presenta un método para caracterizar los estados locales en la superficie y las interfaces en los cristales, así como estructuras epiteliales de baja dimensión basadas en materiales semiconductores. Para ello, se presenta un modelo teórico para explicar dicho espectro de reflectancia diferencial (AODR). También se realizaron experimentos con estructuras de GaAs epitelial contaminado con Teluro (Te). Los resultados teóricos y experimentales obtenidos muestran que este método es una buena herramienta para caracterizar las trampas superficiales en estructuras epiteliales de semiconductores.

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INTRODUCTION

Currently, one of the most important materials for optoelectronics and microelectronics is gallium arsenic (GaAs). It has a number of electrophysical properties and characteristics much better than those of silicon, first, higher electron mobility and prohibited zone. That results in some potential advantages of solid state devices based on GaAs in comparison with those based on silicon. Among them, we can mention higher radiation resistance, higher operation speed, wider range of operational temperatures, lower power consumption. In addition, there are good perspectives for developing new integrated optoelectronic devices based on a single GaAs wafer.

Many experimental techniques are used for characterization of local states in bulk microelectronics materials. Several methods have been used to study crystal lattice defects in semiconductors. These defects including impurity contamination introduce energy levels in the forbidden bandgap. These energy levels in $A_3 B_5$ and $A_2 B_6$ compounds are responsible for variations in the material response to electrical, optical, photoelectric, and acousto-optic excitations. These variations can be utilized to characterize defect levels in a similar manner as other experimental methods such as photoconductivity decay (Bube, 1960), impedance measurements (Nicollian and Brews, 1972), deep level transient spectroscopy (Lang, 1974), and transient capacitance measurements (Chantre *et al.,* 1981). To study semicon-

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ductor properties including the surfaces and interfaces one can also use the acousto-electric measurements (Benabdeslem 1990, Tabib-Azar 1991, Abbate 1993). Nevertheless with the help of the acousto-electric measurements one can precisely read only the deep levels. New development of an experimental technique for semiconductor characterization by using surface acoustic waves was reported in a recent publication (Fritz and Brennan, 1997), but the fractional modulation reflectance signal was very small, of the order of $5x10^{-5}$. This makes it difficult to characterize the shallow states at room temperature, which is important for some applications.

Other innovative experimental techniques including the modern scanning tunneling microscopy (STM) technique, allows characterizing only the atomic structure of the surfaces themselves so and it is difficult to investigate interfaces and interface defects. However, reliable experimental techniques for characterization of shallow levels of interfaces are still lacking. At the same time, it is well known that the quality and electrical properties of low-dimensional and epitaxial semiconducting structures are strongly affected by crystal defects located at the interfaces between epitaxial layers and substrates.

This work is aimed: 1) to study the influence of an ultrasonic wave (UW) on optical reflectance near band to band transitions, and 2) to characterize the shallow trapping levels in epitaxial GaAs:Te by the acousto-optic technique. We present both theoretical and experimental results on complex perturbed acousto-optic reflectance measurements and show this technique allows characterizing shallow levels defect states in epitaxial semiconductor structures.

THEORY

Physical basis of this experimental technique is the interaction of UW with a near surface and interface region in semiconductor structure. This interaction can physically be explained by two different mechanisms. First is an interference of local stresses. We mean local stresses near an interface itself, and ultrasonically generated dynamical stresses. Second mechanism is of an electrical nature, and is due to an interaction of an electrical charge with electrical fields generated by UW. Speech shows some redistribution of charge carriers by UW due to it's electrical action via piezoelectric or deformation electrical potential. Direct evidence of such a kind of electrical interaction is a generation of a transient acoustoelectric voltage (TAV) in epitaxial GaAs by UW propagating in this structure (Abbate *et al.,* 1995). The TAV is produced by ultrasonic activated redistribution of electric charges in semiconductors. So, this redistribution must influence optical reflectance as well. Below, we consider these two ultrasonic actions.

a) Deformation effects. An ultrasonic wave (UW) of frequency f and amplitude U_0 ($U = U_0 \exp[i(2\pi ft - kr)]$) produces in a media an ultrasonic deformation S_U as follow.

$$SU = (dU/dr) = (2\pi U_0 / \lambda)\ exp[i(2\pi ft - kr - \pi/2)]) \qquad (1)$$

where is designated: $k = \omega/v = 2p/\lambda$ - wave number of UW.

For comparison of deformations caused by crystal defects and ultrasound, it is necessary to compare their peak values. Theoretical estimations by using known equations (Teodosiu, 1982) show, that on distances of several inter atomic periods (m) from crystal defect, the deformations near dislocation (*Sd*) and around point defect (*Sp*) will be of the order of:

$$S_d \sim (5/m)\cdot 10^{-2}, \qquad (2)$$

$$S_p \sim (16/m^3)\cdot 10^{-2}. \qquad (3)$$

Thus, on distances about ten inter atomic periods the local deformations from defects equal to 10^{-3} - 10^{-4} are quickly increased at approach to defect. It is important to note that in previous experiments with ultrasound nonlinearity it has been shown at $S_U \sim 10^{-5}$. Such deformations correspond to distances of thousand inter-atomic periods from dislocation, or about thirty periods from an isolated point defect. Thus, both ultrasound and crystal defects cause significant local deformations which influence dielectric permeability and refractive index of media. As a consequence, a reflection of light from a real crystal is changed compared to a defect free solid.

b) Electrical field. In case of piezoelectric crystals of the type of GaAs (also A_2B_6 compounds of C_{6V} symmetry like CdS) a piezoelectric effect is a driving force of affecting in free charge carriers. Note that so called acousto-resistive effect (Gulayev, 1972), consist of a change in resistance due to UW influence on the electron collision mechanisms, and is not the only possible cause for optical constants change. This effect can lead to a small change in resistance, which is smaller than for materials like GaAs which has a high electron mobility. Considering the electrical fields associated

with UW, one can cite three sources of electrical field inside the sample, these are; piezoelectric effect in a crystalline substrate like GaAs, electrical field of charged dislocations vibrating under UW action and last deformation potential field. This last, has a very small magnitude compared to piezoelectric and dislocation effects, and so we can neglect it in our consideration for piezoelectric crystal GaAs.

It is easy to show that normal component of piezoelectric field is not equal to zero at the surface of GaAs wafer. The boundary conditions for a surface UW propagating in epitaxial material can be written (Ostrovskii, 1995) as follows:

$$T_{ij}\, n_j = \left[c_{ijkl} \frac{\partial U_1}{\partial x_k} - e_{m,ij} E_m \right] n_j = P_{ij}\, n_j \qquad (4)$$

where T_{ij} are the components of elastic stress; c_{ijkl} are the elastic constants; $e_{m,ij}$ are the piezoelectric constants; n_j is the vector-normal to the surface; U_l is a displacement in UW, E_m is the piezoelectric field of UW at wafer surface. The right term of eq.(4) ($P_{ij}\, n_j$) is due to a pressure of epitaxial layer on a crystalline substrate. From eq.(4) we can see that acoustic deformation (dU_1 / dx_k) causes a piezoelectric field E_m.

In our samples, an epitaxial layer is deposited on a (100) crystallographic surface of GaAs crystalline substrate. A piezoelectric ceramic transducer for longitudinal vibrations as shown in fig.1 excites an UW. In this geometry, a zero mode of Lamb waves is excited and it propagates in (100) crystallographic plane along [001] direction. The acoustical displacements U_1 and U_3 are not equal to zero. We can write this plane wave as following:

$$U_i = U_{oi}\, exp[i(2\pi ft - kz - k\beta x)] , \qquad (5)$$

where U_{oi} is an amplitude of displacements; f and k are frequency and wave number of UW in GaAs plate, respectively; β - parameter which describes a variation of acoustic wave amplitude along [100] direction. The vector-normal n_j is oriented along the direction [100]. As a result, an UW causes the non-zero acoustical dynamical stresses S_1, S_3 , and S_5 inside the crystalline GaAs wafer including the interface region ($S_{ij} = \partial U_i / \partial x_j$; i and j change from 1 to 3, and a couple ij changes from 1 to 6). By substituting a wave (5) into eq. (4) with $n_j = n_1$, we get the following piezoelectric fields generated by UW in a crystal.

$$E_1 = (C_{55}\, S_5 - P_5)\, e_{11}^{-1} \qquad (6)$$

$$E_3 = (C_{11}\, S_1 + P_1)\, e_{31}^{-1} \qquad (7)$$

In the equations (6,7) the term P_1 represents a pressure of epitaxial film on a substrate; it is directed anti parallel to x-axis. The term P_5 is due to mechanical stresses originated from a mismatching between a crystal lattice of the substrate and layer deposited on that substrate. Thus we see an UW in GaAs wafer or low-dimensional structure causes the piezoelectric fields with the normal component E_1 and tangential component E_3. This electric field accompanying UW can affect free charges and shallow levels in a sample. The first terms in the equations (6,7) are the alternative piezoelectric fields due to UW, and the second terms $P_{1,5}$ are some contribution due to thin layer on the surface. An electric field generated by UW is alternative and changes its direction each half period of UW, but the integral effect is not negligible. Due to the electrical charge trapped by shallow centers and bending of energy bands two anti parallel directions are not equal in action by piezoelectric field. Under these conditions a new equilibrium state between charge trapped on shallow levels and free charge takes place. It gives some change in sample conductivity, as well as change in electrical and optical activity of shallow level defects.

The effects ascribed are also enforced by the dislocations. We have to add the dislocations vibrating in a UW field as an additional cause to produce a redistribution of charge in the sample. In other words, UW produces a redistribution of carriers between shallow trapping centers and conduction/valence bands via its deformation action on media itself and on charged dislocations.

To sum up this consideration we can conclude that effect of ultrasonic action on a crystal consists of the dynamic mechanical stresses and electrical fields. Both factors together bring the changes in crystal conductivity and dielectric constant that in turn leads to variations in electrical and optical activities of shallow defects.

We can summarize an action of UW on a semiconductor structure as a combination of the mechanical (or ultrasonic) pressure, electrical fields, and conductivity change. In addition, under respectively high ultrasonic intensities, we can mention a possible generation of electrically charged defects, and local changes of temperature inside the sample. These ultrasonically induced changes lead to alteration of the sample polarizability, conductivity, dielectric constant, and reflectance. As a result of the above UW actions the electrical and optical properties of a crystal are changed. First, the

dielectric constant becomes an amplitude function of UW (A), $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}(A)$. Second, the differential acousto-optic reflectance ΔR is the difference between ultrasonically perturbed one $R(A)$ and its initial value R_0:

$$\Delta R = R(A) - R_0, \tag{8}$$

The optical reflectance from a conductive media is a function of a complex dielectric constant $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_r - i\boldsymbol{\varepsilon}_i$, and reflectance variation can be presented as a sum of two terms that are proportional to the variations in $\boldsymbol{\varepsilon}_r$ ($\Delta\varepsilon_r$) and $\boldsymbol{\varepsilon}_i$ ($\Delta\varepsilon_i$) (Cardona, 1969). In our case these variations are dependent on ultrasound amplitude A and ultrasonically changing susceptibility x and crystal conductivity σ.

$$(\Delta R(A)/R_0) = [\beta_r \Delta\varepsilon_r(x,A) + \beta_i \Delta\varepsilon_i(\sigma,A)] \tag{9}$$

where x is a real part of crystal susceptibility, and the coefficients β_r and β_i are so called partial Seraphin coefficients, which formally describe a dependence of a reflectance on some perturbation factor leading to dielectric constant variation. They can be presented as the derivatives: $\beta_{r,i} = \partial\, lnR/\partial\boldsymbol{\varepsilon}_{r,i}$ (Cardona, 1969). In a general case we have to take into account volume and surface effects in reflection variation. As for expression (9) we take into account an integral action of UW and light on a wafer by choosing a general form of the partial coefficients $\beta_{r,i}$. A complex dielectric constant in our case of ultrasonic action and optical illumination by light with photon energy $\eta\omega$ can be written:

$$\boldsymbol{\varepsilon}(A, \sigma) = \boldsymbol{\varepsilon}_r(x) - i\boldsymbol{\varepsilon}_i(\sigma) \tag{10}$$

where $x = x(\omega, A)$ is a crystal susceptibility, $\sigma = \sigma(\omega, A)$ is a conductivity of a sample, ω - frequency of light. Acoustically introduced changes in $\boldsymbol{\varepsilon}_r$ and $\boldsymbol{\varepsilon}_i$ can be represented by variations in crystal susceptibility α and initial conductivity σ_0. Ultrasonic influence leads to changes in ion displacements including those in optical phonon modes (ζ_i) and these variations lead to a variation of crystal susceptibility (Δx). In general Δx is a tensor (Davydov, 1976) which can be written as a sum $\Delta x_{lj} = -\Sigma\, B_{lj,i}\, \zeta_i$, where $B_{lj,i}$ are some coefficients. We note that UW can effectively interact with optical phonons in two different ways; lattice anharmonicity and the electric fields caused by acoustic wave. As a result, ζ_i is proportional to a square of UW amplitude. For our consideration an essential fact is that time average $(\Delta x_{lj})^t$ leads to appearance of $\Delta\varepsilon_r$. From this we can get that for certain mode of acoustical vibrations and crystal orientation a following proportionality between $\Delta\varepsilon_r$ and A is valid

$$\Delta\varepsilon_{r,lj} = 4\pi (\Delta x_{lj})^t = -2\pi\eta\, B_{lj} A^2 \tag{11}$$

where η is the nonlinearity parameter. Some of the coefficients B_{lj} can be equal to zero, but normally they remain unchanged, and for certain polarizations of the acoustic and electromagnetic waves we have a following general expression:

$$\Delta\varepsilon_r = -2\pi\eta BA^2 \tag{12}$$

Because in a nonperturbed sample $\varepsilon(\sigma_0) = \varepsilon_r + i(4\pi\sigma_0/\omega)$ (Born and Wolf , 1964), an imaginary part of dielectric constant is altered via crystal conductivity change ($\Delta\sigma$):

$$\Delta\varepsilon_i = -4\pi\Delta\sigma(\omega,A)/\omega \tag{13}$$

Previous experiments (Gulayev, 1972 and Ostrovskii, 1995) showed that $\Delta\sigma$ increases with ultrasound amplitude. This effect is due to some ionization of local centers by UW. Summarizing this analysis by substituting the equations (12,13) in eq. (9) we get a general dependence of the acousto-optical differential reflection (AODR) spectrum on acoustic wave amplitude A.

$$(\Delta R(A)/R_0) = -2\pi\,[\eta\beta_r BA^2 + 2\beta_i \Delta\sigma(\omega,A)/\omega] \tag{14}$$

According to eq. (14), AODR consists of practically non dispersion first term and spectrally dependent second term. The first term slightly varies with light energy due to electronic contribution to the static dielectric constant (Harrison, 1980). The second term is due to crystal conductivity changes as a result of UW action on a sample illuminated by monochromatic light. A concentration of electrical charge carriers and in turn crystal conductivity is proportional to light absorption in a sample. For our consideration the absorption with shallow states in a gap is most important. That is because shallow levels under study are formed by some local states due to crystalline defects like shallow donors, acceptors, antiside defects, and their complexes, etc. Here we consider a case of some types (t) of shallow centers for which a light absorption α is given as following (Seeger, 1973):

$$\alpha\eta\omega \sim N_t^i\, [\eta\omega - (E_g - \Delta E_t)]^{1/2} \tag{15}$$

where N_t^i is a concentration of ionized shallow states, index t represents different types of shallow levels. As we can see, the bands of AODR occur just at light energy $\eta\omega_t = (E_g - \Delta E_t)$. By measuring such spectra one can detect the shallow levels near the conduction and valence bands.

We have also noted that the detection of shallow levels by other known experimental techniques is a rather difficult task, especially at a room temperature

that is desirable for possible practical applications. In optical absorption a bulk part of a sample gives a main contribution, and not a near surface or interface region which is very important for epitaxial low dimensional structures. Optical reflection itself at room temperature can not detect the shallow levels at all. In principle, one can use a low temperature photoelectric and optical measurements, but a question always occurs about the physical origin of a signal read. The point is a photoelectric current is formed in a respectively thick near surface region including a part of a bulk, like optical absorption. In the case of AODR a signal detected is directly connected to the variations in a system of shallow levels located at the interface region.

EXPERIMENT AND DISCUSSION

These experimental measurements were carried out with samples of epitaxial gallium arsenide doped by Te for creation of nonequilibrium donors. The ions of Te having nuclear mass 128 and ionic radius another than arsenic can produce the local deformations around that doping species. Therefore we can assume the samples of GaAs:Te are characterized by stronger local deformations of a crystal lattice in comparison with non intentionally doped GaAs. The characteristics of the samples are the following. The epitaxial layers were deposited by a MBE method on a single crystal substrate GaAs, on a [100] surface. The thickness of layers varied from 2,5 up to 9 microns for different samples and the concentration of electrons was 2.6E15 up to 5E16 cm^{-3} at room temperature.

The Samples were shined from a lamp through a monochromator with light [$J(\eta\omega)$]. The Reflected light [$R(\eta\omega)$], was collimated on a computer aided system for photoelectric registration. The whole experiment and further processing of the data obtained was carried out with the help of computerized optical system. The experimental setup is given in Figure 1. The ultrasonic piezoceramic transducers (3,4) are attached to a sample on its substrate side (2) while an epitaxial layer (1) remains free. Different transducers were made from PZT ceramics, and can excite ultrasonic waves in a frequency (f) range from 100 kHz up to 8 MHz. Ultrasound is generated when applying rf-frequency voltage $V(f)$ to the transducer 4 showed in Figure1. At operation frequencies a platelet of Lamb's waves were excited in the gallium arsenic wafers. In order to prevent an influence of a high-frequency voltage from rf-generator to our experimental samples, we attached a backside of the substrate to a ground contact of a transducer, as is shown in Figure 1.

In our experiments, the spectra of reflected light [$R(\eta\omega)$] was registered under light energies near a forbidden zone of GaAs. Both signals: the initial spectrum R_0 without ultrasound and the spectrum R_V(A) under ultrasonic action on a sample were measured. The differential AODR spectra was calculated from these two as:

$$(\Delta R / R_0) = (R_V(\mathrm{A}) - R_0)/ R_0 \qquad (16)$$

We use the various amplitudes of rf-voltage V(f) from 10 up to 70 Volts V_{pp} for registration of reliable experimental data. Note that by using different UW amplitudes we observe that the main contribution of the output signal was provided by different shallow levels. This effect can be explained as a partial ionization of local states caused by the ultrasound. So, more deep energetic levels are revealed under higher UW amplitudes, and vice versa. The typical experimental results are presented in Figure. 2 for the sample GA4i8. Experimental data are shown by the solid lines marked as 1, 2, and 3 for three amplitudes of ultrasound, which corresponds to three amplitudes of driving voltage $V_1<V_2<V_3$. We can see that AODR is really negative, and different bands are dominating in the plots. There are spectral parts with some bands labeled as E_1 to E_6, and some constant parts represented by total shift of AODR down with an increasing of UW amplitude. The small UW amplitude (plot 1 for rf-voltage V_1) gives a maximum AODR of 4 %, but a respectively higher UW amplitude (plot 3 for V_3 = 2.1 V_1), produces higher maximum AODR of 22 %.

The bands labeled $E_{1,2,3}$ appeared to be clear extremes, but the $E_{4,5,6}$ are located at some shoulders only. To make a spectral resolution more evident we also registered a photo-AODR spectrum under an illumination of yellow photo diode. The later one increases a concentration of free charges and in turn the concen-

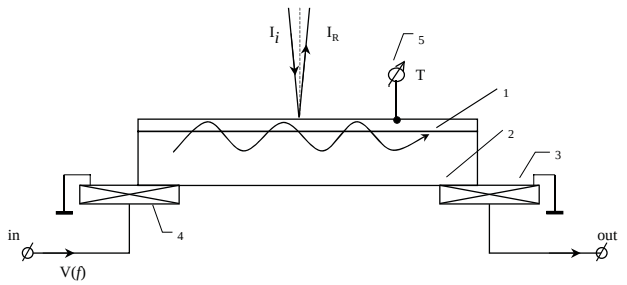

Figure1. Experimental setup. 1 – epitaxial layer, 2 – substrate, 3 and 4 – input and output piezoceramic transducers, 5 – thermocouple, I and R – incident and reflected light respectively.

trations of captured local states charge carriers. As a result, we revealed the shallow states which were not good resolved in ordinary AODR spectra of Figure 2. The experimental results with additional photo illumination are shown in Figure 3 by solid squares. The dashed and doted lines in Figure 3 are the results of computer decomposition of the experimental AODR-spectrum on the separate spectral components. A special program for optical spectra processing carried out the analysis and computer simulation. As we can see from Figure 2 and Figure 3, the whole set of six peaks E_1 to E_6 are presented in the AODR signal. It is necessary to note, that the experimental results were taken from several samples (GA - 3, 4, 5; GA4-i7,8), and under consecutive number of rf-voltage amplitudes that excited ultrasound in the samples. The obtained results appear to be of the same type, as is shown in Figure 2, and Figure 3. The spectral position of the E_1 to E_6 peaks differs very little, on some meV. Quantitatively speaking, this difference is less than 10 % for E_2 - E_6 lines, and more for shallow E_1 state. The differences between a spectral width of a forbidden zone (1,428 eV) and subsequent maxims of the strips $E_{1\text{-}6}$ give the ionization energies ($\Delta E_{1\text{-}6}$) of the shallow local states, or in other words their energetic positions with respect to the forbidden zone limits. Our experimental data and a comparison with those known from literature are presented in Table1.

The dispersions for $E_{1\text{-}6}$ and so $\Delta E_{1\text{-}6}$ values taken from different samples and ultrasound amplitudes are presented in the column 5 named *"dispersion"*. As can be noted the values oscillate between 3 meV and 7 meV. For analysis we have taken into consideration a set of known shallow levels in the forbidden zone, donors and acceptors, from the literature (Hilsum 1961, Berg 1979, Neu 1999, Wakaya 1998, Ziebro 1992, Yu 1983. Elliot 1982, Zhang 1990). These data are shown in the columns 6 and 7 of Table1. They are: 1) E_2 is due to an impurity Zn_{Ga}. Another, more early, description of this level is (E_C - 30 meV) - donor owing to crystal doping with Te; 2) E_3 = (E_C - 45 meV) - level of arsenic vacancy (V_{As}); 3) E_5 = (E_V + 78 meV) - level of gallium in arsenic site (Ga_{As}). Here E_C means a bottom of a conduction zone, and E_V - top of a valence zone. 4) Peak E_6 can be attributed to the surface states (SS_2 in Table1), according to recent theoretical calculation (Wakaya, 1998). The comparison of the experimentally registered shallow levels corresponding to the peaks $E_{2,3}$, $E_{5,6}$ to known defects levels (Hilsum 1961, Berg 1979, Neu 1999, Wakaya 1998, Ziebro 1992, Yu 1983. Elliot 1982, Zhang 1990) allows us to identify experimentally observed local states, which is presented in the column 6 of Table1.

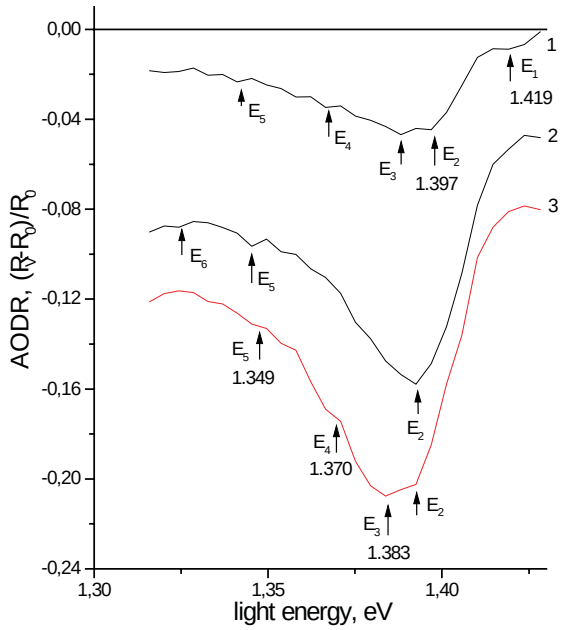

Figure 2. AODR from GaAs:Te at different ultrasound amplitudes. Sample GA4i8 UW frequency 3.46 MHz, V_{pp}(f) = 16 Volts for plot 1, 29 for 2, 34 for 3.

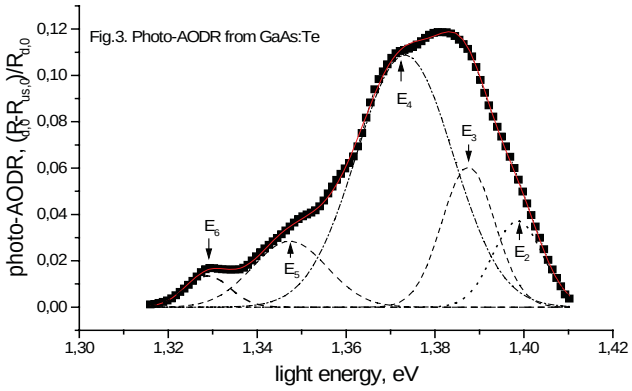

Figure 3. Photo-AODR from GaAs:Te. Sample GA4i8, UW frequency 3.45 MHz, V_{pp}(f) = 33 Volts. Dashed lines – computer decomposition of experimental spectra for gauss components.

As we see from Figure 2, 3 and Table1, there are two shallow levels having ΔE_1 and ΔE_4 that are not uniquely identified for the GaAs:Te epitaxial structures. Theoretical calculation show (Wakaya, 1998) there is in GaAs materials a shallow surface state of 5 meV due to rupture on a free surface. Because in our case we have the interface between a crystalline substrate and an epitaxial layer, we can suppose this

Table1.
Experimental data and identification.

N	peak E_t	maximum E_t[eV]	ionization energy ΔE_t,[meV]	dispersion, [meV]	identification	Reported in Previous works ΔE_t [meV]
1	**2**	**3**	**4**	**5**	**6**	**7**
1	E_1	1.419	9	+- 3		
2	E_2	1.397	31	+- 3	Zn_{Ga}	30.7
3	E_3	1.383	45	+- 4	V_{As}	45
4	E_4	1.370	58	+- 5		
5	E_5	1.349	79	+- 4	Ga_{As}	78
6	E_6	1.328	100	+- 5	SS_2	100

shallow surface state can be modified to have the ionization energy ΔE_1 = 9 meV instead of 5 meV for a free surface. Another explanation may be given in connection with theoretical calculation (Hilsum 1961) of ionization energy for shallow donor in GaAs that was estimated as 8 meV.

Analyzing the peak E_4 , we have to note that corresponding ionization energy ΔE_4 = 58 +-5 meV coincides with some of the phonon groups in GaAs that take part in optical absorption. For example, energy of (LO+LO) phonons revealed in a light absorption is exactly 58 meV. So this shallow state can be attributed to the crystal phonons, especially in the presence of ultrasound in a sample.

CONCLUSIONS

The Acousto-Optic Differential Spectra presented here were measured with the help of ultrasonic perturbation of shallow states in semiconducting materials. A photo-AODR technique consisting of double action of ultrasound and light on a matter turns out to be an effective tool for shallow level characterization. To the best of our knowledge this experimental technique was not discussed or published earlier. By measuring AODR and photo-AODR one can characterize the shallow states in the wafers and epitaxial structures at room temperature. A theoretical explanation of this effect is given.

Experiments have been performed on epitaxial GaSa:Te using different ultrasonic amplitudes and frequencies. A dispersion of experimentally measured AODR bands is 5 +- 2 meV for the ionization energies of local centers of 10 meV to 100 meV.

We find the shallow levels at the interface between epitaxial layer and a substrate known for a bulk GaAs material, they are impure shallow level E_2, structure defect E_3 , anti-structure defect E_5. Thus the defects of a bulk material can exist at the interfaces in the epitaxial structures. The surface state (E_6 in Table 1) is also revealed that proofs the theoretical calculation (Wakaya, 1998). The peak E_1 corresponding to the ionization energy 9 meV is detected. We do not find the experiment studies claming that shallow surface state in GaAs based materials.

The detected peak E_4 corresponding to the ionization energy equal to the longitudinal optical phonons (LO+LO) suggests that phonon energies should be taken into account when considering the shallow states at the interfaces. An additional argument for that is a strong dependence of E_4 amplitude on ultrasound intensity. This component increases rapidly with UW amplitude increase. Such behavior can be explained by nonlinear interaction between UW and phonons, and subsequent increase in phonon density. In particular, it is important for acoustically driven devices based on GaAs material like Acoustic Charge Transport devices. This point is important because above results demonstrate in higher ultrasonic power regimes the shallow phonon related states can effectively capture the charges and cause a distortion of the charge packet in a ACT device.

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