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SURFACE ACOUSTIC WAVE SPECTROSCOPY INVESTIGATION OF ELECTRICAL PROPERTIES OF THE NEAR-SURFACE REGION GaAs CRYSTALS

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The possibility of the appyling the surface acoustic wave of Rayleigh type to semiconductor investigations is described. The transverse acoustoelectric effect has been used to study the real surfaces of GaAs:Cd (111) and GaAs:Si (110) single crystals. The semiconductor surface in the layered structure: piezoelectric wave guide-semiconductor were performed. These investigations for different surface acoustic wave (SAW) frequencies were carried out. The values of the electric surface potential Φ_s the carrier density n_S as well as the effective life time τ_e of the minority carriers were obtained. The investigations were performed in a 50÷200 MHz frequence range. The dynamic values of these semiconductor surface parameters in a high frequency acoustic wave range were presented. The results have shown that the electrical and electron surface parameters may be various for different frequencies.

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1. Introduction

The electrical and electronic properties of the near-surface semiconductors region are completely different then its volumetric ones. Very often this region decides about the possibility of semiconductor crystal applications in technology of electronic devices and of their applications as the sensing elements for variety sensors techniques [1,2].

The semiconductor surface properties may be determined by means of the electrical sufrace potential Φ_S carrier density n_S and life time τ_e of minority carriers in the near surface region [1].

For the technology of electronic devices more and more often the III–V group semiconductors are used. In this group the GaAs crystal is a very important target material, first of all for its interesting optical properties. This semiconductor is used among other things technology of laser diodes and non coherent light sources, as well as for very high frequency amplifiers and for different senors construction [3].

The maximum of the work temperature for GaAs is twice as large as for Si and it is about 200 °C. The maximum of the work frequency of electronic GaAs devices may be even five times as large as of Si ones.

The development of the solid state spectroscopy causes the interest of using the acoustic methods in the semiconductor surface investigations. The surface acoustic wave methods seem to be a good tool for the semiconductor surface experimental investigations in high and very high frequency ranges.

When the surface acoustic wave (SAW) propagates in the piezoelectric-semiconductor structure, then the electric field, which accompanies this wave, penetrates the near-surface region of this semiconductor. (The penetration depth of the electric field inside the semiconductor is of the order of the extrinsic Debye lenght or the acoustic wavelenght, whichever is shorter). This electric field changes the free carrier concentration in the semiconductor near-surface region and causes drift of these carriers. There are plenty of aspects of the interaction between surface acoustic wave and charge carriers [4]. Among others, the difference of electrical potentional between the semiconductor surface and its bulk (i.e. transverse acoustoelectric voltage TAV) may be observed [5].

The transverse acoustoelectric method is very useful and attractive one for determination of semiconductor surface parameters. This method is non destructive one, it does not require ohmic contacts and give the dynamic values of investigated parameters.

The influence of the electron and electrical surface parameters on the character of transverse acoustoelectric effect (the amplitude of TAV and its time shape) were already earlier observed. In [6] it was shown that the monitoring of the acoustoelectric voltage or SAW attenuation while varying the conductivity by external means (e.g by temperature) can yield information about the density of the surface and impurity states in the semiconductor. By observing the optical wavelength dependence of the acoustoelectric voltage developed across the semiconductor one may have the information about energy profile of the states in the band gap. The transverse acoustoelectric voltage has been measured as a function of incident photon energy in InAs on $LiNbO_3$ SAW delay line structure in [7]. From the experimental results the energy band gap in InAs was determined. In [8] the transverse acoustoelectric voltage spectroscopy for the GaAs:Cr samples was performed. The samples were illuminated by two monochromatic beams. The characteristic exciton peak was observed at temperature below 200 K. Using two beam light illumination of the investigated semiconductor sample, one could determine the presence of donor and acceptor levels in the band gap of the GaAs:Cr sample. The similar technique of TAV used together with the illumination and temperature changes of GaP and InAs samples was presented in [9]. The deep levels in band gap of the investigated semiconductor samples were presented. This kind of investigations of the energy levels in the near-surface region in a semiinsulating GaAs was also reported in [10]. The acustoelectric measurements allow a precise determination of surface trap level distribution in the silicon band gap at the Si/SiO_2 interfaces [16]. Two kinds of experiments were presented there: the effect of an uniaxial compression and the effect of

HCl annealing are monitored by transverse acoustoelectric voltage versus voltage. The results indicate the presence of three energy levels in the energy midgap.

In the paper [11] we applied the longitudinal and transverse acoustoelectric effects to determine the surface potential in Si nad GaAs crystals. The results of the theoretical analysis of both acoustoelectric effects were described. The new acoustoelectric method of the surface potential determination was also presented. For the high resistivity GaAs: Te samples the values of surface potential were nearly — 0.4 [V]. The experimental results have shown that the acoustoelectric effects, particulary the transverse acoustoelectric effect, may be used for investigations of semiconductor surface properties. In [12, 13] the transverse acoustoelectric effect and the surface photo-voltage effect have been applied to the study of the GaP real surfaces. The values of the effective life time of minority carriers after different surface and their diffusion length have been presented.

The works mentioned above are not the only ones of these kind, of course. We think that the cited papers are important in the domain of application of surface acoustic waves and transverse acoustoelectric effect to semiconductor surface investigations.

In this paper the transverse acoustoelectric effect has been used to study the real GaAs:Cd (111) and GaAs:Si (110) surfaces. The real surface of a semiconductor means the surface obtained after cutting, polishing and standard chemical etching of the crystal. Such surfaces appear at different steps of the semiconductor surface preparation for devices technology. In this paper the investigations of the surface potential Φ_S, the carriers density n_S as well as the effective life time τ_e of the minority carriers in the near-surface GaAs regions have been presented.

2. Theoretical model

The transverse acoustoelectric voltage has been described by the following theoretical formulas [11,13]

$$U_{AE}=K\frac{\mu_p^2 p_b-\mu_n^2 n_b+n_i\frac{L_i}{L}(\mu_n^2 G_n-\mu_p^2 G_p)}{\mu_p p_b+\mu_n n_b+n_i\frac{L_i}{L}(\mu_p G_p-\mu_n G_n)}R. \tag{2.1}$$

$$R=\frac{\omega(\mu_n n_b+\mu_p n_b)+n_i\frac{L_i}{L}(\mu_p G_p-\mu_n G_n)}{\varepsilon_0^2(\varepsilon_S+\varepsilon_p)^2\ \omega^2+q^2\left[\mu_p p_b+\mu_n n_b+n_i\frac{L_i}{L}(\mu_p G_p-\mu_n G_n)\right]^2}. \tag{2.2}$$

$$u=\frac{q\Phi}{k_B T},\quad u_S=\frac{q\Phi_S}{k_b T},\quad u_b=\frac{q\Phi_b}{k_b T}. \tag{2.3}$$

where: μ_n, μ_p mobilities of electrons and holes, respectively, in the near surface region

n_b, p_p concentrations of electrons and holes in the bulk of the semiconductor,
n_i electron concentration in the intrinsic semiconductor,
n, p concentrations of electrons and holes ($n=n_b e^{V}$; $p=p_b e^{-V}$)
L_i, L intrinsic and effective Debye lenght, respectively
G_n, G_p Kingston functions of the second type for electrons and holes [15]
Φ electric potential in semiconductor [1, 2, 15]
Φ_S electric surface potential (at the sufrace $\Phi=\Phi_S$)
Φ_b electric potential inside the semiconductor (in the bulk $\Phi=\Phi_b$,)
ε_p, ε dielectric constants of the piezoelectric and semiconductor
ω acoustic wave circular frequency
q electron charge

The Kingston Functions G_n, G_p, carrier mobilities μ_n, μ_p, as well as concentrations of electrons and holes n, p, are complicated functions of the surface potential Φ_S and electron concentration n_S in the near-surface region. (The nonelementar Kingston functions: G_n, G_p may be numerically calculated: they are presented in the graph and in the graph and in the tables [1, 15].)

The theoretical analysis of the acoustoelectric effects were presented in [11, 13]. The teoretical results of this analysis are used for the determination of the electron concentration n_S and the surface potential Φ_S in the next part of this paper.

The surface theoretical and experimental investigation results presented here were obtained for the samples with the following bulk parameters:

i) GaAs:Si (110)
- n-type electrical conductivity
- carrier mobilities: $\mu_n = 8200$ [cm²/V*s], $\mu_p = 410$ [cm²/V*s]
- permittivity: $\varepsilon = 10.4$
- band gap: $E_g = 1.48$ eV
- electron concentration: $n = 1.2*10^{14}$[cm^{-3}]
- resistivity: $\rho = 3.6*10^{6}$ [Ωcm]

ii) GaAs:Cd (111)
- n-type electrical conductivity
- carrier mobilities: $\mu_n = 8600$[cm²/V*s], $\mu_p = 400$[cm²/V*s]
- permittivity: $\varepsilon = 9.8$
- band gap: $E_g = 1.44$ eV
- electron concentration: $n = 1.2*10^{15}$[cm^{-3}]
- resistivity: $\rho = 3.0*10^{5}$[Ωcm]

In Fig. 1. the theoretical function of the amplitude U_{AE} versus carrier density n_S in the surface region for GaAs:Si (110) is presented. This function was calculated using the theoretical results which we presented in [15]. For the GaAs:Cd (111) sample, the theoretical function $U_{AE} = f(n_s)$ was very similar to this one presented in Fig. 1.

For very high carrier concentrations, near the intrinsic region, the interactions between the electric field (from SAW in piezoelectric) and carriers in the near surface region are very small. The TAV voltage, as the results of this interactions, are very

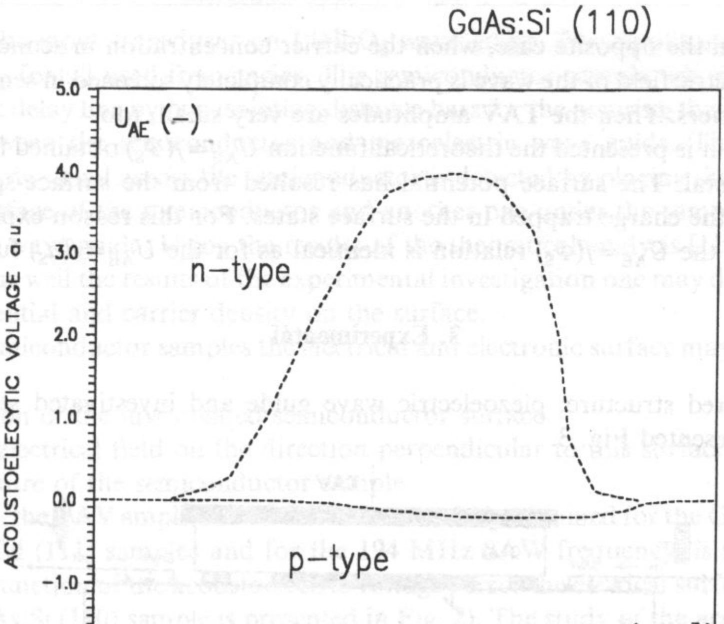

Fig. 1. The transverse acoustoelectric voltage as the theoretical function of the carrier concentration in near-surface region.

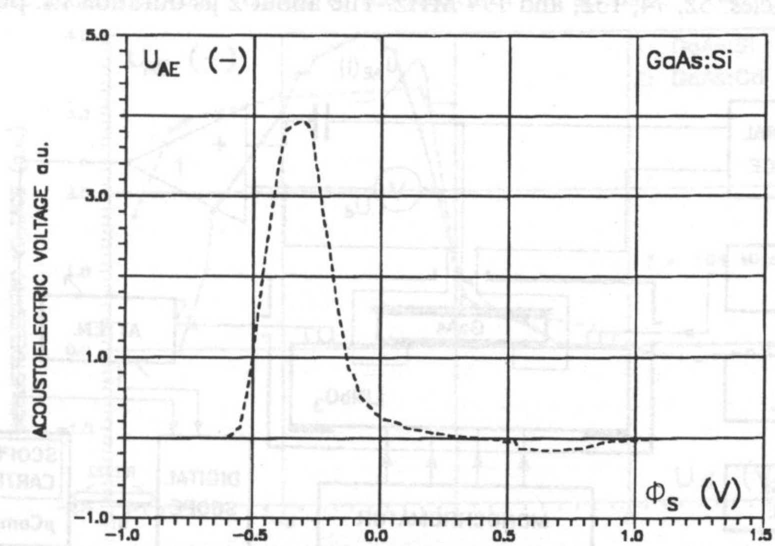

Fig.2. The theoretical relation $U_{AE}=f(\Phi_S)$ for GaAs:Si (110).

small, too. In the opposite case, when the carrier concentration in semiconductor is large, the electric field of the wave is practically completely screened in semiconductor by these carriers. Then the TAV amplitudes are very small, too.

In Fig. 2. it is presented the theoretical function $U_{AE}=f(\Phi_S)$ obtained for the same GaAs:Si crystal. The surface potential has resulted from the surface-space charge neutralising the charge trapped in the surface states. For this reason explantation of the shape of the $U_{AE}=f(\Phi_S)$ relation is identical as for the $U_{AE}=f(n_S)$ function.

3. Experimental

The layered structure: piezoelectric wave guide and investigated semicoductor sample is presented Fig. 3.

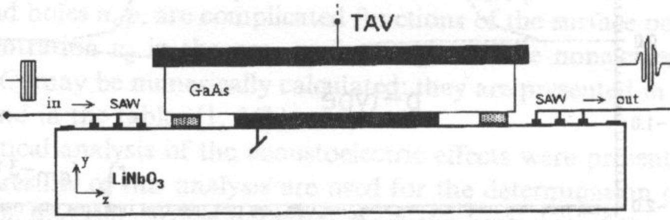

Fig. 3. The scheme of the layered structure: piezoelectric wave guide and investigated semiconductor.

The set-up for the surface semiconductor investigation by means of the transverse acoustoelectric method is shown in Fig. 4. The investigations were performed for the four frequencies: 52, 74, 132, and 194 MHz. The about 2 μs duration r.f. pulse was

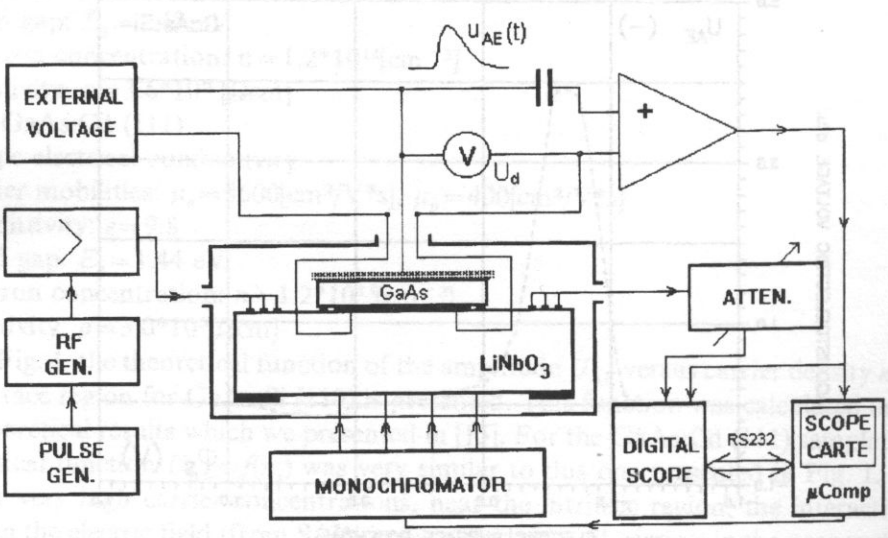

Fig.4. The experimental set-up for the semiconductor surface investigation by TAV method.

applied to the input transducer on $LiNbO_0$ wave guide. The amplitudes of the r.f. pulse 3.5 [V] for all used frequencies. The semiconductor sample was placed at the piezoelectric delay line by two isolating distance bars for the assuring the non acoustic contact between the semiconductor and piezoelectric wave guide. The transverse acoustoelectric signal across the semiconductor is detected by placing the Al plate on the back surface of the semiconductor and another one under the sample placed on the acoustic wave guide. Using the results of the theoretical analysis [11], Eqs. (2.1), (2.2), (2.3), as well the results of the experimental investigation one may determine the surface potential and carrier density on the surface.

In the semiconductor samples the electrical and electronic surface may be changed by [11]:

i) illumination of the investigated semiconductor surface
ii) external electrical field on the direction perpendicular to this surface
iii) temperature of the semiconductor sample

In Fig. 5. the TAV amplitude versus the external U_d, obtained for the GaAs:Si (110) and GaAs:Cd (111) samples and for the 194 MHz SAW frequency, is shown. (The theoretical function of the acoustoelectric voltage versus the eletrical surface potential for this GaAs:Si (110) sample is presented in Fig. 2). The study of the acoustoelectric effects versus the external voltage U_d were cared out for four surface wave frequencies (52, 74, 132, 194 MHz). For higher frequency the U_{AE} amplitude was larger. Frist of all, these effects result from the fact that for higher SAW frequency its wave length is smaller and the interaction distance between acoustic wave and charge carriers in semiconductor is effectively longer. The same semiconductor length contains larger number of the acoustic wave length for a higher frequency. For this reason we relate the transverse acoustoelectric voltage to the length of the acoustic wave.

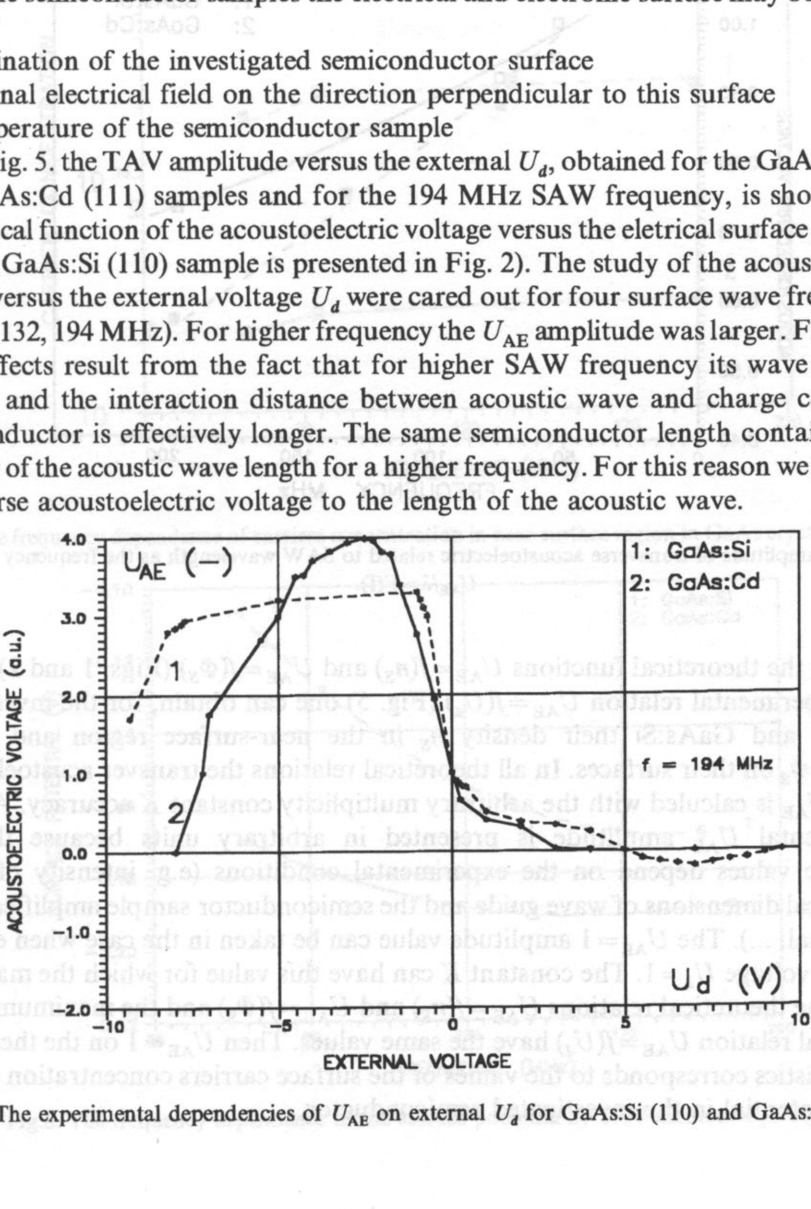

Fig.5. The experimental dependencies of U_{AE} on external U_d for GaAs:Si (110) and GaAs:Cd (111).

In Fig.6 we present the dependence of the TAV amplitude referred to the wave length versus the SAW frequency: $U_{AE}/\lambda = F(\omega)$. The values of U_{AE}/λ are presented in arbitrary units and the value $U_{AE}/\lambda = 1$ is related to the 52 MHz frequency. This relation seems to proof that higher frequency the trapping of carries by energetic surface states are strong — plenty of carriers interact with these states, there are located in band gap and smaller part of carriers interact with SAW and TAV amplitude U_{AE}/λ are smaller for higher frequency.

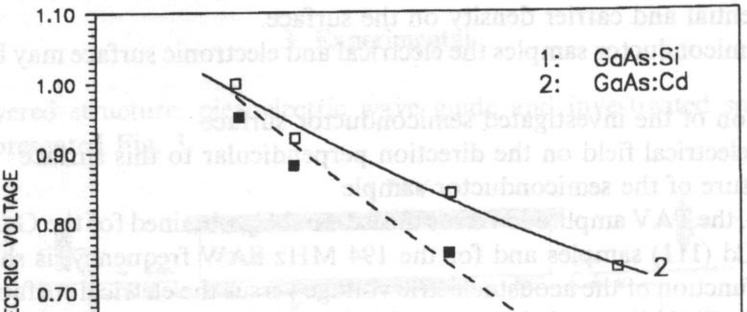

Fig.6. The amplitude of transverse acoustoelectric related to SAW wavelength as the frequency function: $U_{AE}/\lambda = F(f)$.

Using the theoretical functions $U_{AE} = f(n_S)$ and $U_{AE} = f(\Phi_S)$ (Figs. 1 and 2) as well as the experimental relation $U_{AE} = f(U_d)$ (Fig. 5) one can obtain, for the investigated GaAs:Cd and GaAs:Si their density n_S in the near-surface region and electric potential Φ_S on their surfaces. In all theoretical relations the transver acustoelectrical voltage U_{AE} is calculed with the arbitrary multiplicity constant K accuracy. Also the experimeental U_{AE} amplitude is presented in arbitrary units because the U_{AE} amplitude values depend on the experimental conditions (e.g. intensity of SAW, geometrical dimensions of wave guide and the semiconductor sample amplification of TAV signal, ...). The $U_{AE} = 1$ amplitude value can be taken in the case when external electrical voltage $U_d = 1$. The constant K can have this value for which the maximum U_{AE} on the theoretical relations $U_{AE} = f(n_S)$ and $U_{AE} = f(\Phi_S)$ and the maximum on the theoretical relation $U_{AE} = f(U_d)$ have the same values. Then $U_{AE} = 1$ on the theoretical characteristics corresponds to the values of the surface carriers concentration and the surface potential in the investigated semiconductor.

For the higher frequency the surface potential have the smaller values. The frequency dependencies of the carrier concentration in the near surface region for GaAs:Si (110) and GaAs:Cd (111) are show in Fig.7. In Fig. 8 the surface potential versus frequency is presented. One may see that electric field from SAW in piezoelectric wave guide changes the carrier concentration in the conducting band.

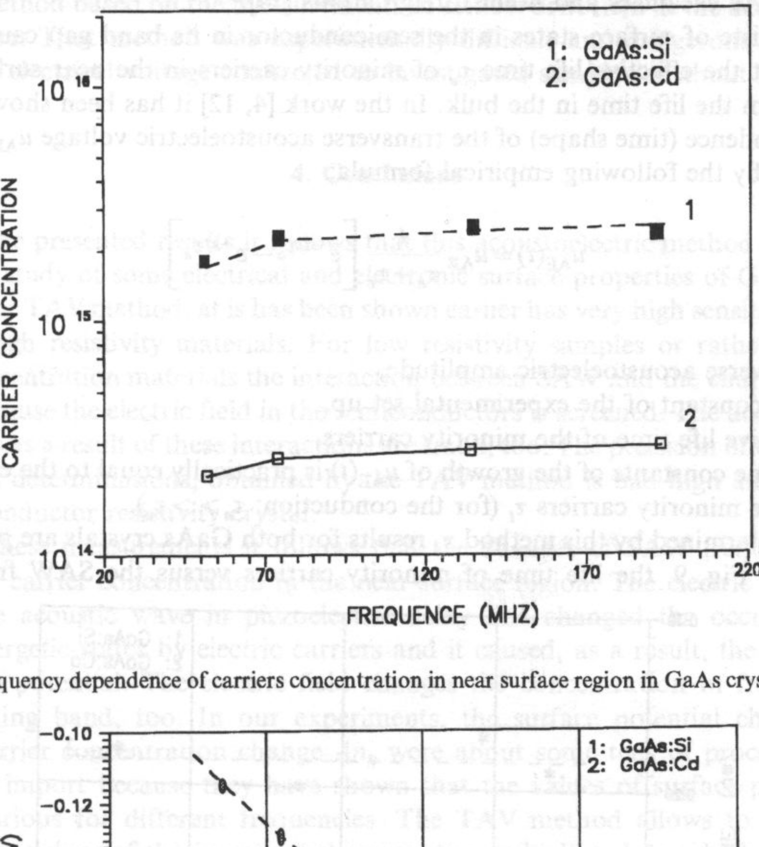

Fig.7. The frequency dependence of carriers concentration in near surface region in GaAs crystal $n_S = F(f)$.

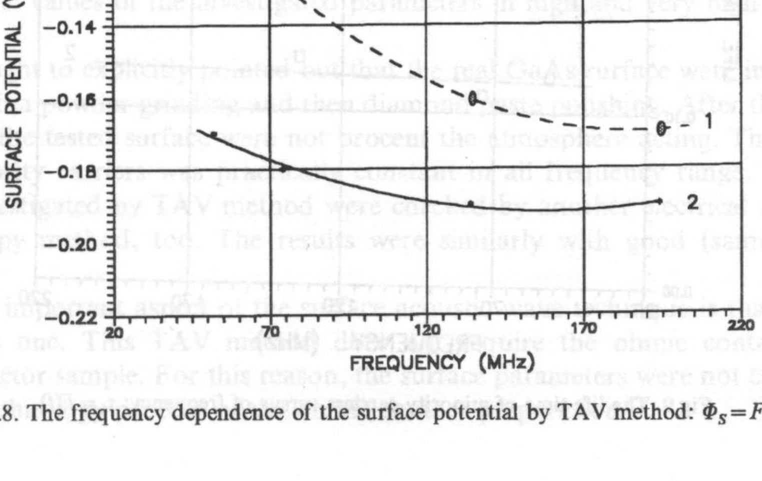

Fig.8. The frequency dependence of the surface potential by TAV method: $\Phi_S = F(f)$.

For our high resistivity GaAs:Cd and GaAs:Si samples with higher frequency the carrier concentration n_S was lower.

The surface states acting as recombination centres or as traps evoking the surface potential barriers can be produced by lattice defects, chemical contaminations (e.g. oxygen, carbon dioxide and hydrogen adsorption), oxidation or complexes formed from Ga, As vacancies and other foreign atoms [19].

The existe of surface states in the semiconductor in its band gap causes among others that the effective life time τ_e of minority carriers in the near surface region differs from the life time in the bulk. In the work [4, 12] it has been shown that the time dependence (time shape) of the transverse acoustoelectric voltage $u_{AE}(t)$ may be described by the following empirical formula:

$$u_{AE}(t)=u_{AE}\frac{t}{\tau_a-\tau_e}\left[e^{-t/\tau_a}-e^{-t/\tau_e}\right]$$

where

U_{AE} transverse acoustoelectric amplitude,

τ_a time constant of the experimental set up,

τ_e effective life time of the minority carriers.

The time constants of the growth of $u_{AE}(t)$ is practically equal to the effective life time of the minority carriers τ_t (for the conduction: $\tau_a >> \tau_e$).

The determined by this method τ_e results for both GaAs crystals are presented in Fig. 9. In Fig. 9. the life time of minority carriers versus the SAW frequency is

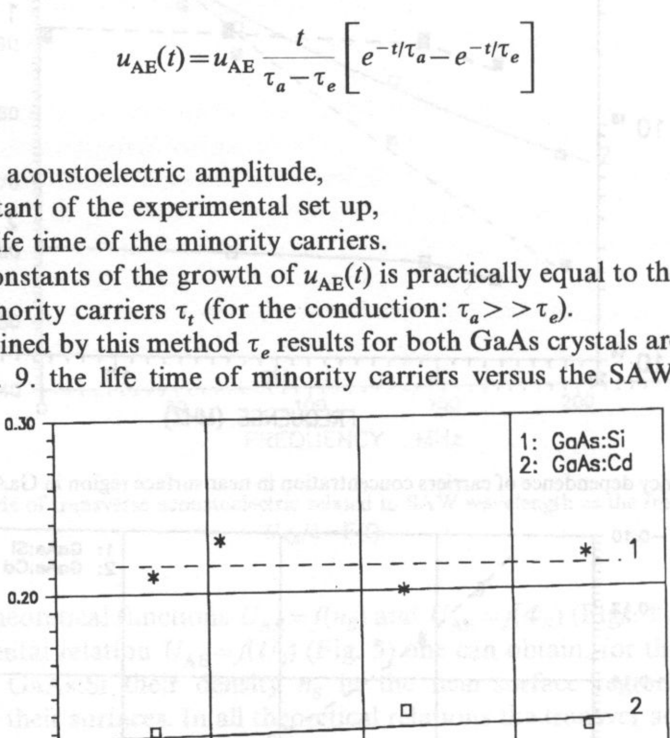

Fig.9. The life time of minority carriers versus of frequency: $\tau_e = F(f)$.

presented. In [12] it was used this τ_e determination method for GaP samples. The values of effective life time of minority carriers τ_e obtained TAV method were verified by the surface photo-voltage method. The results of τ_e determined by both these methods (TAV and photo-voltage) were similar with good accuracy (about ten procent). In the work [19], the life time τ_e for Si samples was obtained by means acoustic method based on the measurements of critical drift field in the acoustoelectric structure. That method was experimentally difficult and dangerous because it needed the electrical voltage connected to investigated samples of about $2 \div 3$ kV.

4. Conclusions

From the presented results it follows that this acoustoelectric method is a useful tool in the study of some electrical and electronic surface properties of GaAs single crystals. The TAV method, at is has been shown earlier has very high sensitivity in the study of high resistivity materials. For low resistivity samples or rather for high carrier concentration materials the interaction between SAW and the charge carriers is weak because the electric field in the semiconductors is screened. The acoustoelectric voltages as a result of these interactions are small, too. The precision of the surface parameters determinations, obtained by the TAV method is bad high and for very low semiconductor resistivity crystal.

From these measurements it follows that the changes of SAW frequency may change the carrier concentration in the near-surface region. The electric field from the surface acoustic wave in piezoelectric delay line changed the occupation of surface energetic states by electric carriers and it caused, as a result, the change in the surface potential. The electric field changes the concentration of free carriers in conducting band, too. In our experiments, the surface potential change $\Delta\Phi_S$ and the carrier concentration change Δn_S were about some tens of procent. These results are import because they have shown that the values of surface parameters may be various for different frequencies. The TAV method allows to determine the dynamic values of the investigated parameters in high and very high frequency ranges.

One ought to explicitly pointed out that the real GaAs surface were investigated after alumina powder grinding and then diamond paste polishing. After this surface treatment the tested surface were not procent the atmosphere acting. The life time τ_e of minority carriers was practically constant in all frequency range. The parameters investigated by TAV method were checked by another electrical and photo spectroscopy method, too. The results were similarly with good (same procent) accuracy.

A very important aspect of the surface acoustic wave technique is that it is non destructive one. This TAV method does not require the ohmic contacs to the semiconductor sample. For this reason, the surface parameters were not changed by difficult technology procces of the ohmic contact preparation.

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