INVESTIGATIONS OF THE NEAR-SURFACE REGION IN *INAS* BY MEANS OF SURFACE ACOUSTIC WAVE TECHNIQUES

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Fast development of micro- and nanoelectronics is connected with development of various sensor and measurement techniques, and requires searching of new research methods.
A possibility of applying the surface acoustic waves of Rayleigh type for the investigations of semiconductor surface is described in this paper.
The theoretical relations between the transverse acoustoelectric voltage, the surface electrical conductivity and the surface potential in InAs single crystals are presented.
The experimental results of the surface investigations performed by means of the transverse acoustoelectric voltage method, after various surface treatments of the InAs (111) samples, are also presented.
These measurements enabled us to establish a strong influence of chemical and mechanical surface treatment upon the values of the surface parameters in InAs crystals.

1. INTRODUCTION

The development of the micro- and nanoelectronics causes an increasing interest in application of the acoustic methods in the semiconductor surface investigations.

This follows from the prospective possibility of using of acoustic methods for the technology of electronic devices. It seems that the surface acoustic wave methods may be a useful, non-destructive tool for the semiconductor surface research in high and very high frequency range.

Generally, these methods are based on the interaction between the surface acoustic waves of the Rayleigh type and the free carriers in the semiconductor. This interaction occurs realised in the layered structure: the piezoelectric waveguide and the semiconductor [1,2,3].

The electrical and electronic semiconductor surface properties may be determined by means of the surface potential, the carrier trapping velocity by fast and slow energetic surface states, the type of impurity atoms and molecules, their concentration and location in the energy gap in the target material, as well as by the surface mobility of carriers and the lifetime of majority and minority carriers [4].

In the technology of electronic devices, silicon is the commonly used material, but the III-V group semiconductors become more and more popular. This follows from the very interesting optical properties of these new materials. Indium arsenide is used for laser diodes construction. The coherent and non-coherent light generators were elaborated by using the electroluminescence effect observed in InAs. The electrical and electronic InAs properties, mainly the very high of mobility carriers, make it possible to construct of the electronic devices in higher frequency range.

Applying the galvanomagnetic effect in InAs the hallotrons and gaussotrons were constructed [4,5]. This material is also often used in various sensors applications [6].

In the group of methods for the semiconductor surface investigation, there are no methods which determine the surface parameters in high frequency ranges. There exists the high frequency field effect method, but its measurement possibility is practically restricted to some MHz [7].

For this reason the InAs surface investigations in high frequency range were not performed.

The paper presents the theoretical and experimental surface investigations of InAs (111) surface by means of transverse acoustoelectric effect.

2. SURFACE ACOUSTIC WAVE FOR SEMICONDUCTOR SURFACE INVESTIGATIONS

When the surface acoustic wave (SAW) propagates in the piezoelectric semiconductor structure, the electric field, which accompanies this wave, penetrates near- surface region of the semiconductor. The penetration depth of the electric field inside the semiconductor is of the order of the semiconductor extrinsic Debye length or the acoustic wavelength (whichever is shorter). This electric field changes the free carrier concentration in the near-surface region of the semiconductor and causes a drift of the carriers [8].

In piezoelectric waveguide the changes of acoustic wave velocity and the changes of attenuation, as a result of acoustoelectric interaction are observed [8, 9, 10].

The theoretical analysis of the acoustoelectric amplifier [9] allowed to elaborate the new acoustic method of determination of the carriers lifetime in the fast surface energetic states and the velocity of the carriers trapping by fast surface states in semiconductors [11]. The results of the experimental investigations of high resistivity Si (111) crystals were presented in [12].

From the measurements of zero values of the electron attenuation in the acoustoelectric amplifier structure, one can determine the mobility of carriers in the near-surface region [12, 13].

In semiconductor, as a result of interaction between the electric carrier and the surface acoustic waves (SAW) the followning phenomena may be observed:

a) the electric current in the direction of surface wave propagation (i.e. longitudinal acoustoelectric effect LAE) [14],

b) the difference of electric potentialis between the semiconductor surface and its bulk (i.e. transverse acoustoelectric voltage TAV) [15-17].

In [15] the theoretical analysis of both acoustoelectric effects (LAE and TAV) was presented. These results created the theoretical basis for new acoustic methods of determination of the surface potential in semiconductors [16].

The experimental results of the surface potential as well as the lifetime of minority carrier investigations in some GaAs and GaP crystals performed by means of longitudinal and transverse acoustoelectric methods are presented in [17, 18].

The transverse acoustoelectric effect seems to be especially important for semiconductor investigations. From its theoretical analysis [15, 19] it results that in the semiconductors which one type of conductivity is predominant (n- or p-type), the sign of the acoustoelectric voltage depends on the type of electrical conductivity in the near- surface region. If the surface conductivity is negative (n-type), then the transverse acoustoelectric voltage (TAV) has of the positive value and if the surface conductivity is of the p-type, then TAV has a negative value. The results of the conductivity - type investigations for GaP and InP were presented in [20]. The measurement of the sign of TAV voltage is a fast and very easy method of the surface conductivity - type determination.

The transverse acoustoelectric method of semiconductor surface investigation (based on the transverse acoustoelectric effect) is nondestructive [15]. It does not require ohmic contacts on the investigated samples but, first of all, the method provides high values of the frequency surface parameters.

Certain semiconductors of III-V group were investigated by the TAV method.

In [21] the investigation of semi-insulating GaAs in low temperature and with different surface wave power was reported.

Using the TAV methods we have studied different semiconductor crystals, such as : GaAs [22], GaP [23], InP [24] crystals. To our knowledge, there are no papers dealing with these methodes of surface investigations.

In this paper the experimental results of the surface investigations of InAs (111) crystals after various surface treatments are presented, as well as the results of theoretical analysis of TAV concerning the surface electrical conductivity and the surface potential.

It should be mentioned that there are several other papers where the problems of electrical properties of semiconductors were studied by means of the SAW methods.

We think that the .papers quoted above are important in the domain of application of the SAW method in semiconductor surface investigation.

3. EXPERIMENTAL

The set-up for the surface semiconductor investigation by means of the transverse acoustoelectric method is shown in Figs 1 and 2.

The layered structure consists of the tested semiconductor is presented in Figs 1a and 1b.

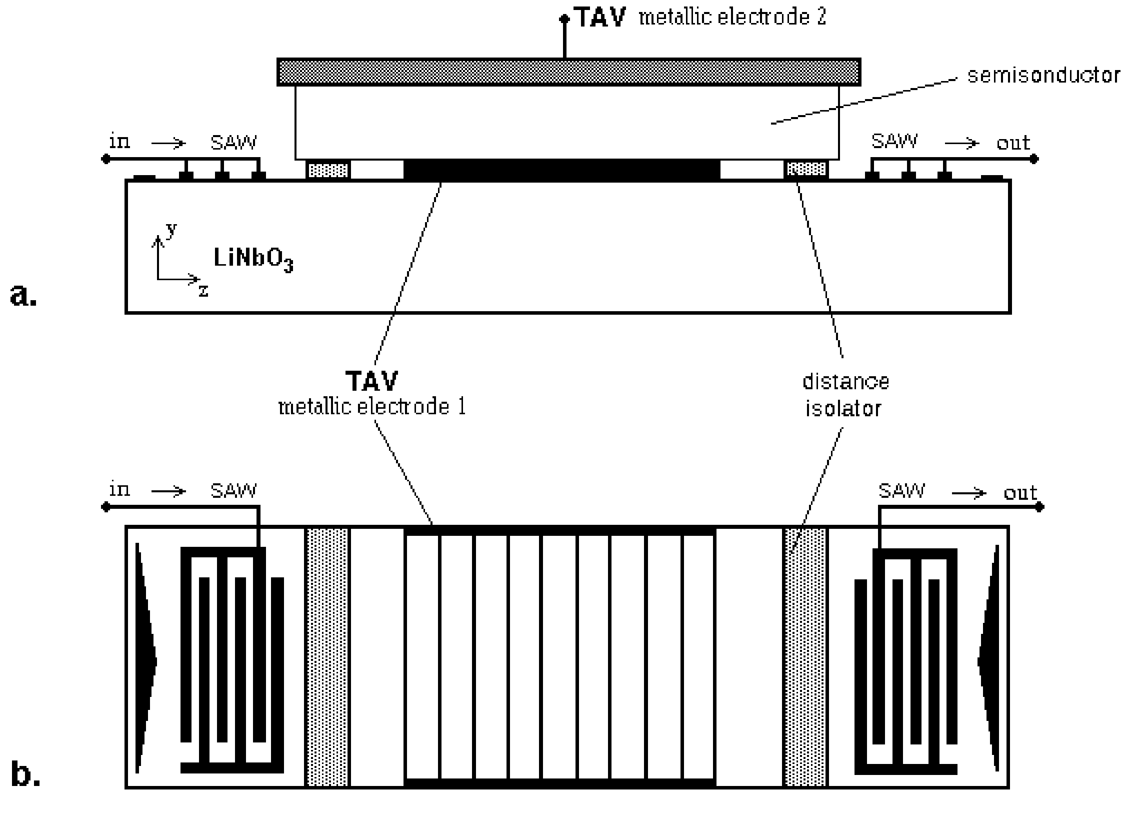

Fig1.a,b. The schematic presentation of the layered structure: piezoelectric wave guide and investigated semiconductor.

The short (some μs duration) impulses of 134 MHz are applied to the input interdigital transducer to generate the surface acoustic wave (SAW) on the Y-cut, Z- propagating in $LiNbO_3$ delay line. The semiconductor is placed at the surface of the delay line by the isolating distance bars for assuring a non-acoustic contact between the semiconductor and the piezoelectric waveguide. The transverse acoustoelectric signal (TAV) across the semiconductor is detected by placing one Al plate on the back surface of the semiconductor (TAV electrode 2), and another one under the semiconductor sample placed on the acoustic wave guide (TAV electrode 1). The thickneses of the TAV electrode 1 and the isolating distance bars are about 400 nm.

In order to provide the best contact between the investigated semiconductor surface and the TAV electrode 1, this electrode consists of narrow strips (Fig. 1b). The width of a single metallic strip is ~ $2{\cdot}10^{-2}$ mm and the distances between them are about 0.5 mm.

The distance between the strips is much larger than the acoustic waveength ($\lambda{\approx}2.5{\cdot}10^{-2}$ mm), and for this reason the TAV electrode1 is not essential for the SAW propagation and does not disturb it. The TAV electrode 1 in the form of a gives a good electric field distribution between both TAV electrodes. It relates to acoustoelectric voltage as well as external voltage $U_{d.}$

In order to change the surface potential value in the investigated semiconductor, we applied to semiconducter thed.c. voltage or the pulse voltage across the TAVelectrodes.
The set-up is shown in Fig. 2.

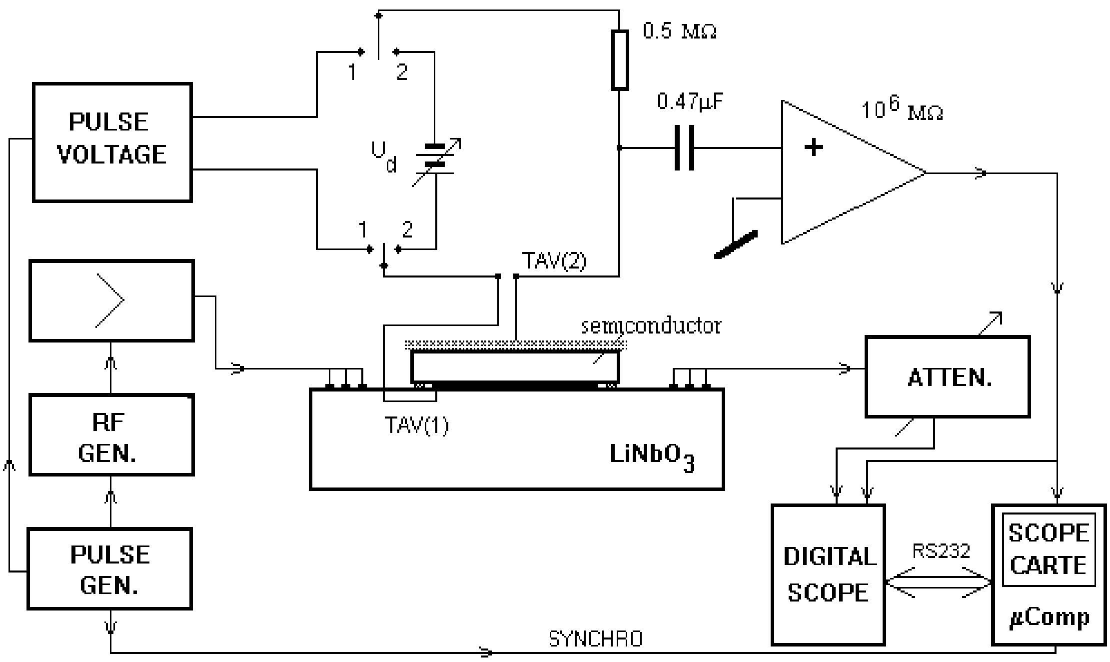

Fig.2 The experimental set-up for the semiconductor surfaceinvestigation by TAV method

For registration of the acoustoelectric voltage, in our set-up we used the digital scope (IWATSU DS-86359) and the computer scope converter(PFS-20)

Using the higher harmonics of the acoustic transducer it is possible to investigate of semiconductors below one GHz.

The interdigital transducers and the aluminium TAV electrode 1 are produced by standard evaporation and photolithography techniques.

The transverse acoustoelectric voltage method was used to investigate the InAs (111) crystal samples with the following bulk parameters:

- n-type electrical conductivity
- carrier mobilities: μ_n = 33 000 $cm^2V^{-1}s^{-1}$, $\mu_p = 460$ $cm^2V^{-1}s^{-1}$permittivity: $\varepsilon = 11.5$,
- band gap : $E_g = 0.44$ eV,
- electron concentration: $N_d = 1.6 \cdot 10^{15}$ cm^{-3},
- resistivity: $\rho = 2.5 \cdot 10^5$ Ωcm.

4. RESULTS AND DISCUSSION

In [22] we have presented the results of our theoretical analysis of the acoustoelectric effects (longitudinal acoustoelectric current and transverse acoustoelectric voltage) in a layered piezoelectric - semiconductor structure. We have shown the theoretical relations between the acoustoelectric voltage on the semiconductor surface parameters such as the surface electrical conductivity and the surface potential.

In Fig. 3 is presented the transverse acoustoelectric voltage (TAV) as the function of surface electrical conductivity in the investigated InAs sample.

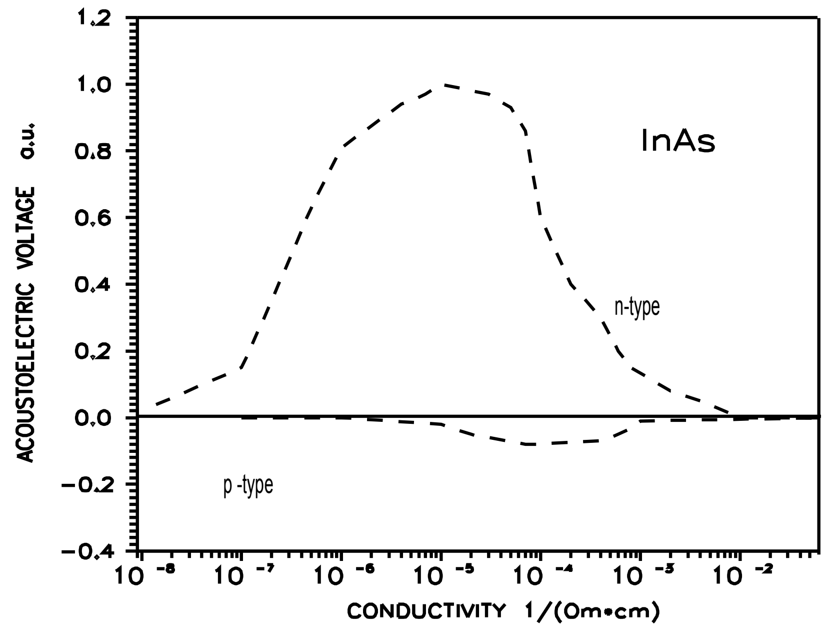

Fig.3 The transverse acoustoelectric voltage as the function of the electrical surface conductivity in InAs

This function was calculated by means of our theoretical results which were presented in [22].

For some values of the p-type surface conductivity the minimum transverse acoustoelectric voltage is observed (about 10^{-4} 1/Ωcm). For the p-type surface electrical conductivity the TAV amplitudes have negative values. Then, starting from ~10^{-2} 1/Ωcm, the amplitude TAV is equal to zero up to ~10^{-8} 1/Ωcm n-type surface conductivity.

Next, the TAV starts to grow, it has positive values of TAV amplitude and reaches the maximum at ~10^{-5} 1/Ωcm. For higher values of conductivity the TAV grows small and for ~10^{-2} 1/Ωcm it is practically equal to zero.

The qualitative explanation of the dependence of this kind is simple.

For very high carrier concentrations, near the intrinsic region, the interactions between the electric field (accompanied the acoustic wave in piezoelectric waveguide) and carriers in the near-surface region are very weak. The TAV, as the results of these interactions are also very small. In the opposite case, if the carrier concentration in the semiconductor is high, the electric field of the wave is practically complet screened by these carriers. Then, the TAV amplitude is also small.

One can see in Fig.3. that the transverse acoustoelectric voltage spectroscopy is a very sensitive method for high resistivity semiconductors. It is an ideal technique to study the InAs samples, because their electrical properties (high resistivity and high carrier mobility) are just in the high sensitivity TAV range.

As it was mentioned before, the electronic properties of the near-surface region may be changed by external electrical voltage perpendicular to the surface. It is a very simple method of influencing the surface semiconductor properties.

In Fig.4 the experimental dependence of the amplitude of the transverse acoustoelectric voltage U_{AE} upon the external voltage U_d for InAs sample is presented.

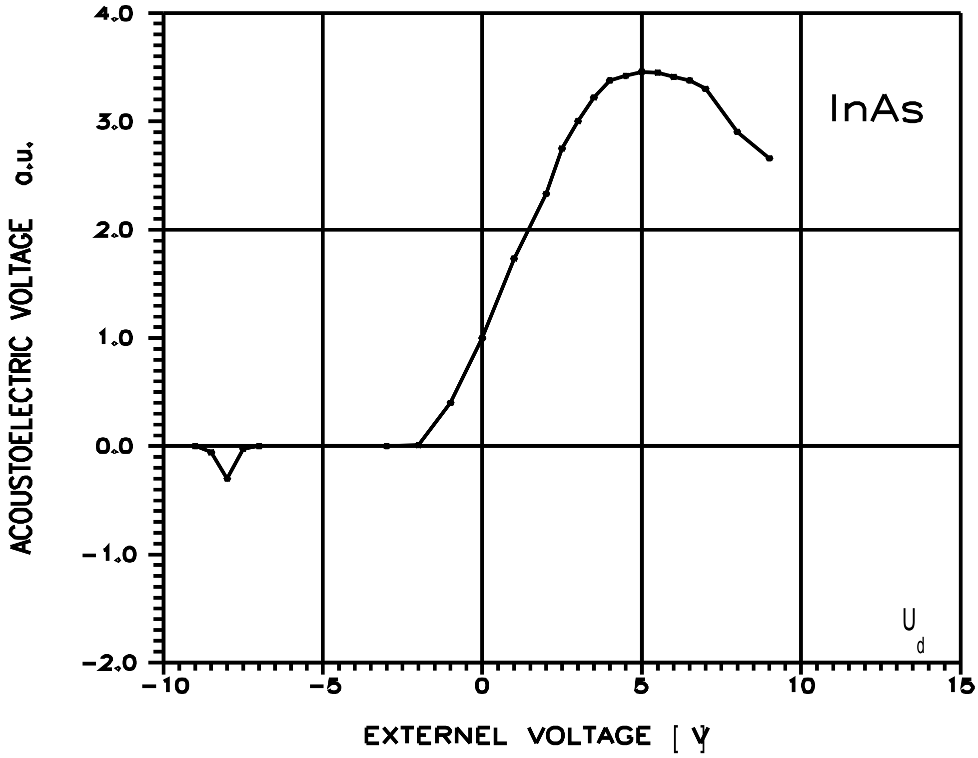

Fig.4 The experimental dependence of U_{AE} on external voltage U_d for InAs surface

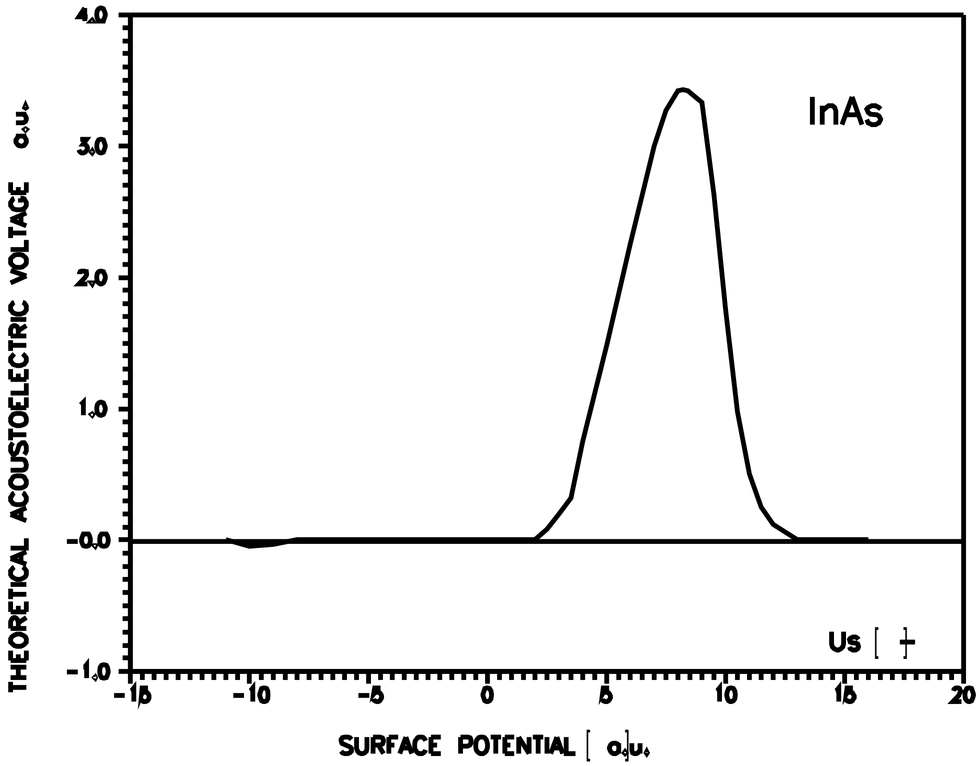

Fig.5 The theoretical dependence of U_{AE} on surface potential U_S for InAs (U_S=$e\Phi_S/kT$)

Fig. 5 shows the theoretical function of the amplitude of TAV versus the surface potential U_S for the InAs singlecrystals. U_S denotes the value of the surface potential in kT units: $U_S = e\Phi_S/kT$ and Φ_S V denotes the surface potential in the semiconductor [7]

The function which is presented in Fig.5 was calculated by using the theoretical relations given in [22]. In order to determine this relation, we needed to know the following bulk parameters presented above: the carriers mobility, carriers concentration, the permittivity and the electrical conductivity for the investigated InAs crystals.

By using both functions: the experimental relation $U_{AE} = f(U_d)$ and the theoretical relation $U_{AE} = f(U_S)$ one may propose the method of determination of the surface potential value in semiconductors (for zero external bias voltage). This method of the surface potential determination was discussed in detail in [18].

The theoretical dependence of the TAV amplitude upon the surface potential U_S is calculated with accuracy up to an arbitrary constant multiplicatier K. (Constant K may be interpreted as the aperture character constant). We may substitute for K the value for which the maximum in the theoretical relation $U_{AE} = f(U_S)$ and the maximum in the experimental relation have the same values. For the experimental characteristic $U_{AE} = f(U_d)$, the value $U_{AE} = 1$ corresponds to the case for which the external voltage U_d is equal to zero. For the theoretical relation $U_{AE} = f(U_S)$, the value $U_{AE} = 1$ corresponds to the surface potential of the investigated semiconductor sample.

For the investigated InAs sample, the value of the surface potential Φ_S obtained by this method was equal to $\Phi_S = -0.11 \pm 0.02$ V.

The transverse component of the electric field of the acoustic wave in piezoelectric waveguide acting on electrical carriers in semiconductors changes its concentration in the near-surface region. The new steady state of the concentration is reached after the time period which depends on the carrier lifetime. The electrical surface semiconductor properties are different from the bulk ones. For this reason the values of lifetime in the bulk and in the surface are quite different, too.

The lifetime of the minority carriers may be determined from the shape of the transverse acoustoelectric signal. It was shown in [15] that the transverse acoustoelectric signal $u_{AE}(t)$ is described by the following mathematical 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.

For the case, when the time constant of the experimental set up τ_a is much greater than the life time of minority carriers ($\tau_a >> \tau_e$), the value of the time constant of the acoustoelectric signal is practically equal to the life time of minority carriers τ_e.

(The condition $\tau_a >> \tau_e$ is usually easy to satisfy.)

By this method the life time τ_e was determined. For InAs sample under investigation the life time of the minority carriers is equal to $\tau_e = 2.0 \cdot 10^{-4}$ s (before the surface treatment).

The experimental measurements of the TAV amplitude versus the surface acoustic wave power allow to estimate how intensive is the influence of the surface processes on the total conductivity of the investigated samples. If the interaction between the electric carriers and surface traps are not intensive then the amplitude U_{AE} versus the acoustic power of the surface acoustic wave is a linear function.

If the interactions of the electric carriers with the surface tarps are intensive than relation $U_{AE} = f(P_{ak})$ is non-linear. [3]

The very important advantage of the acoustolectric effect method is the possibility of the surface examination during the alteration of the surface properties. We think that this fact will allow to control the changes of the surface parameters after various surface treatments due to the technological process.

In [18, 23] we presented the results of the determination of the surface potential, life time of the minority carriers, type of electrical conductivity obtained for Si, GaP and GaAs singlecrystal samples, which are the various bulk and surface properties.

The main purpose of these investigations was the exploration of the influence of the surface treatments for the certain of the surface parameters values. The samples were measured after mechanical and chemical surface treatments which are applied during the technology of electronic devices. We also tested the surface parameters after mechanical grinding by alumna powders with the various granulation of grains and after the polishing with diamond paste.

We also tested the surface parameters after the cleaning of the sample in acetone, benzene, methanol and after chemical etching in HF acid or in $3HNO_3 + 10H_2O_2$. After the surface treatments, the samples were rinsed in methanol and deionized water.

We applied the various combinations of simultaneous mechanical and chemical treatments.

Fig 6 presents the changes of life time of the minority carriers in InAs sample after : a) alumna powder grinding (grains No100) , b) diamond paste polishing, c) HF acid etching

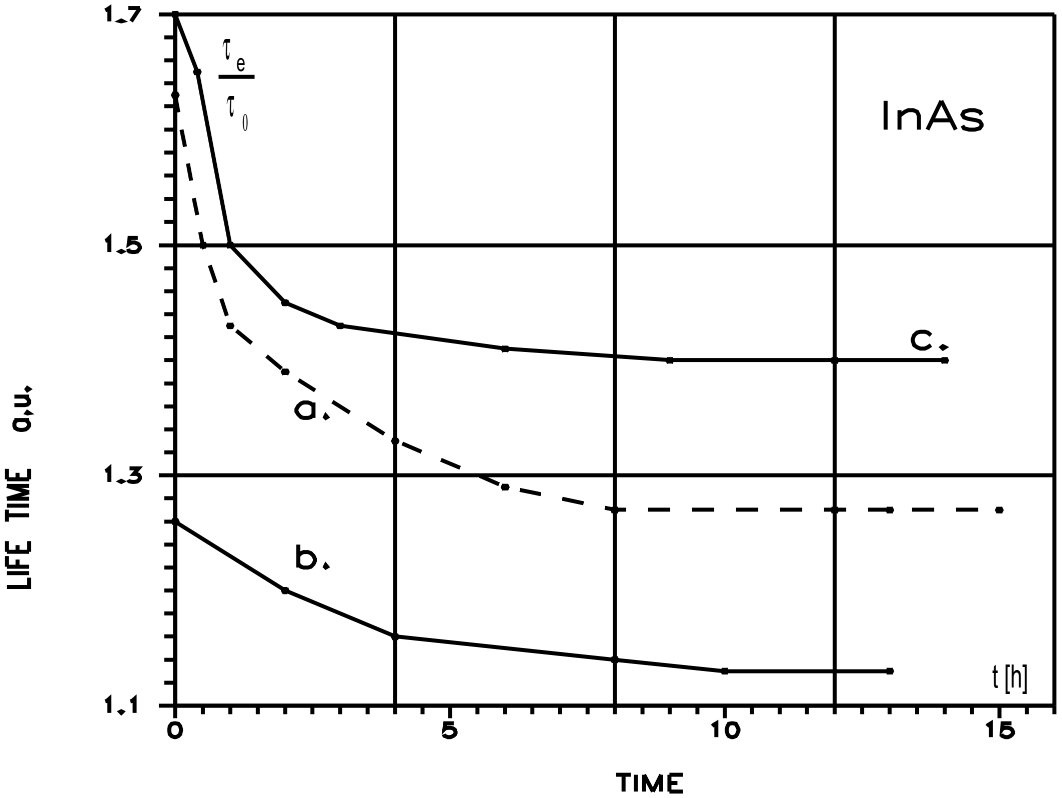

Fig.6 The life time of the minority carriers in InAs after different surface treatment: a) alumna powder grinding, b) diamond paste polishing, c) HF acid etching

From these studies we observed that the carrier life time changed after alumna powder grinding very essentially.

The changing of τ_e stopped after some hours, but with the different steady state values than before the surface treatments.

The steady state value of the minority carriers life time after alumna powder grinding is equal to $\tau_e = 2.5 \cdot 10^{-4}$ s. In Fig.6, the time τ_o denotes the steady state of the minority carriers life time before the surface treatments, equal to $\tau_o = 2.0 \cdot 10^{-4}$ s.

The very long time of the transient state of the life time shows that in the surface processes not only fast surface states take part but also slowly surface states in the oxide layer.

5. CONCLUSION

It follows from the presented results that the transverse acoustoelectric method (TAV) is useful tool for studying the electrical and electron surface properties of indium arsenide. The method allows experimental determination of the surface potential and the effective live time of the minority carriers, as well as the type of the surface conductivity in near surface IaAs (111) region.

We presented also the results of theoretical analysis or TAV versus the surface potential. This theoretical results and experimental relation U_{AE} versus the external voltage U_d allowed the determination of the value of the surface potential in investigated InAs sample by zero bias voltage.

The surface potential determined by means of our acoustic method was equal to $U_S = -0.11 \pm 0.02$ V.

We presented theoretical results of the acoustoelectric voltage versus the electrical conductivity in the near surface region. It follows from this result that TAV is very strong function of the carriers concentration and only for restricted concentration partitions the TAV amplitude are different from zero value. For our InAs (111) sample these concentrations are of the range: $1.3 \cdot 10^{15} \div 7.0 \cdot 10^{16}$ cm^{-3}.

We proved that the values of τ_e were depended on the type of the surface preparation technology. The largest changes of τ_e in InAs sample were observed for mechanic alumna grinding (No 100) and for HNO_3 acid etching. The change of τ_e after these surface treatments were of some tens percents. After cleaning and boiled in different alcoholes, benzene and acetone the life time changes were smaller, about some percents. The smallest changes of τ_e were observed after benzene cleaning (2-3 %). After diamond paste polishing the changing of τ_e were about ten percents.

The Transverse Acoustoelectric Voltage Method is non destructive. Moreover, this method does not require the ohmic contacts to the tested semiconductor samples.

This method provides the possibility to determine the values of the parameters in high and very high frequencyranges.

The presented results were obtained for 134 MHz surface acoustic wave frequency. There are possibility to investigate the surface semiconductor by means of the SAW techniques up to some GHz. The results of the semiconductors surface investigations of III-V group in a very high frequency range were presented in [25].

It follows, from the presented measurements that acoustic methods may be very useful complements for electrical, photospectroscopy and photoemission methods of semiconductor surface investigations.

Indium arsenide is relatively new semiconductor material. This material is used among other, for the technology of luminescence and electroluminescense devices, as well as the target material for laser diodes, hallotrons and gaussotrons.

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