ARCHIVES OF ACOUSTICS
19, 2, 271–280(1994)

INVESTIGATION OF SURFACE POTENTIAL OF GaAs SURFACE BY MEANS OF ACOUSTOELECTRIC EFFECTS

T. PUSTELNY AND Z. KUBIK

Institute of Physics, Silesian Technical University
(44-100 Gliwice, ul. Krzywoustego 2)

The methods of surface potential determination of the semiconductor using the measurements of longitudinal and transverse acoustoelectric effects in the piezoelectric–semiconductor layer structure are presented. When a semiconductor sample is placed in the proximity of a piezoelectric surface acoustic wave (SAW) delay line, the propagating electric field interacts with the carriers in the semiconductor surface. As the results of these interactions the longitudinal and transverse acoustoelectric effects are observed.

The acoustoelectric voltages are strongly dependent on the electrical properties of the near-surface region in semiconductor.

The experimental results of investigations of the surface potential obtained for several GaAs samples are presented.

For all various doped GaAs samples the values of the surface potential of real GaAs surfaces obtained by means of the new acoustic methods were nearly 0.4 [V].

1. Introduction

When the surface acoustic wave (SAW) propagates in the piezoelectric-semiconductor structure, the electric field, which companies this wave penetrates near-surface region of the semiconductor.

The penetration deph of this 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 carriers concentration in the near-surface region of semiconductor and causes drift of these carriers [3, 4, 5].

In semiconductor, the results of the electric carriers and SAW interaction are observed:

— the direct current in the direction of surface wave propagation (i.e. longitudinal acoustoelectric effect LAE) and

— the difference of electric potential between a semiconductor surface and its bulk (i.e. transverse acoustoelectric effect TAV).

The acoustoelectric effects are strongly dependent on the electrical properties of the near-surface region of the semiconductor.

The all SAW measurement techniques of the semiconductor surface investigation use the nonlinear interaction between rf electric field and the free carriers of the semiconductors.

The electrical properties of the surface and the depth of the interaction can be changed by applying an external perpendicular voltage across the semiconductor sample, by changes of its temperature and after the illumination of semiconductor.

For these reasons, the nondestructive Surface Acoustic Wave Technique can be used to study the semiconductor surface properties.

In recent years an interest of acoustic methods for the investigation of semiconductors is observed. Their main advantages consists in non-destructive and quick measurements and after all, the possibility of carrying out the measurement for a wide range of frequency.

By means of the surface wave attenuation measurements (in the piezoelectric–semiconductors layered structure) one can obtained the following parameters of the quick surface states: velocity of surface trapping, effective live time of free charge carriers in traps and approximate value of the surface states concentration [1, 9, 10].

The transverse acoustoelectric voltage is dependent on the wavelength and intensity of light illumination of the semiconductor surface. From these kind TAV measurements one can determine the position of the electron surface states in energy gap [2, 11, 12, 18]. The presented results are interesting since they confirm the possibility of the determination of the position of surface states in the energy gap by means of acoustics and optics measurements what is atractive for semiconductor surface science.

For the theoretical analysis of the acoustoelectric effects in the layered piezoelectric–semiconductor structure the influence of the existing surface potential in semiconductor for the character of acoustoelectric interaction was taken into consideration only fragmentaric. There were small number of theoretical works where, in the final formulae of longitudinal acoustoelectric current I_{AE} and transverse acoustoelectric voltage U_{AE} take into consideration of the charge concentration as the function of u_s potential in near-surface region.

In [3, 4] there made the theoretical analysis of acoustoelectric effects (LAE and TAV) where the charge concentration and mobility of carriers as the functions of surface potential were used.

The theoretical relations $I_{AE} = f(u_s)$ and $U_{AE} = f(u_s)$ are applied for the new original methods of the determination of surface potential in semiconductor. In this work these methods are described. We have examined the surface potential of the real GaAs surfaces. The real surfaces of semiconductor means the surface obtained after cutting, polishing and standard chemical etching of the crystal.

Before our measurements of the acoustoelectric methods (LAE and TAV) the GaAs samples were mechanical grinding with the corund powder then polishing with the diamond paste and cleaning in benzene, methanol and deionized water. The experimental results of the surface potential investigations for the real surface of several GaAs samples are presented.

2. The acoustoelectric effects in piezoelectric—semiconductors structure — The theoretical approach

The electric field of the surface wave penetrates a semiconductor and induces excess carriers and causes their drift, too.

The electric field and excess concentration are wave functions.

The product of them is nonzero. As the results of interaction between excess carriers and electric field the electric currents in semiconductors appear. One of them propagates in the direction of surface wave (longitudinal acoustoelectric current I_{AE}). The another one is perpendicular to the semiconductor surface. At the time corresponds to the Maxwell's relaxation time, the current becomes compensated by means of perpendicular diffusion current. The new unbalanced charge distribution of carriers take place and the difference of electrical potential between a semiconductor surface and its buck is observed (transverse acoustoelectric voltage U_{AE}).

The theoretical analysis of the acoustoelectric phenomenons with consideration of electrical properties semiconductor surface was presented in [4].

The calculated values of the longitudinal acoustoelectric current I_{AE} and transverse acoustoelectric voltage U_{AE} were determined by the following equations.

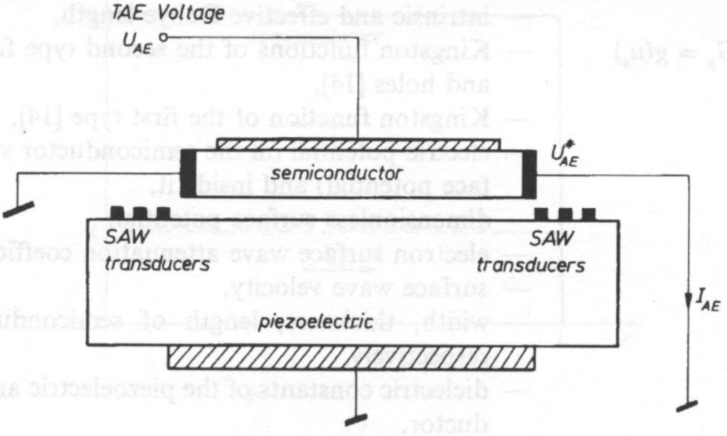

Fig. 1. Experimental setup for the acoustoelectric effects.

$$I_{AE} = \frac{\mu_p^2 p_b - \mu_n^2 n_b + n_i \dfrac{L_i}{L}(\mu_p^2 G_p - \mu_n^2 G_n)}{\mu_p p_b + \mu_n n_b + n_i \dfrac{L_i}{L}(\mu_p G_p + \mu_n G_n)} \frac{2\alpha S b}{V_0}, \tag{1}$$

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

$$R = \frac{\omega(\mu_n n_b + \mu_p n_b) + n_i \frac{L_i}{L}(\mu_p G_p + \mu_n G_n)}{\varepsilon_0^2(\varepsilon_s + \varepsilon_p)^2 \omega^2 + q^2 \left[\mu_p p_b + \mu_n n_b + n_i \frac{L_i}{L}(\mu_p G_p + \mu_n G_n)\right]^2}, \tag{3}$$

$$\alpha = \frac{K_e^2}{2V_0} \varepsilon_p \varepsilon_0 \frac{\omega^2 q \left[\mu_n n_b + \mu_p p_b + n_i \frac{L_i}{L}(\mu_p G_p + \mu_n G_n)\right]}{\varepsilon_0^2(\varepsilon_s + \varepsilon_p)^2 \omega^2 + q^2 \left[\mu_p p_b + \mu_n n_b + n_i \frac{L_i}{L}(\mu_p G_p + \mu_n G_n)\right]^2}, \tag{4}$$

$$u = \frac{q\phi}{k_B T}, \quad u_s = \frac{q\phi_s}{k_B T}, \quad u_b = \frac{q\phi_b}{k_B T}, \tag{5, 6, 7}$$

μ_n, μ_p — mobility of electron and holes, respectively, in the near-surface region

$p_b = n_i \exp(-U_b)$, $n_b = n_i^2/p_b$ — concentration of electrons and holes in the bulk of semiconductor,

n_i — electron concentration in the intrinsic semiconductor,

L_i, L — intrinsic and effective Debye length,

$G_n = f(u_s)$, $G_p = g(u_s)$ — Kingston functions of the second type for electrons and holes [14],

$F(u, u_b)$ — Kingston function of the first type [14],

φ_s, φ_b — electric potential on the semiconductor surface (surface potential) and inside it,

u_s — dimensionless surface potential,

α — electron surface wave attenuation coefficient,

v_0 — surface wave velocity,

b, h, l — width, thickness, length of semiconductor plate, respectively,

ε_p, ε_s — dielectric constants of the piezoelectric and semiconductor,

ω — wave circular frequency,

q — electron charge,

k_d — coefficient of diffusive dispersion of charge carriers on the semiconductor surface

m_p, m_n — effective mass of hold and electrons,

S, K — constants.

For specifying the above expressions one can introduce the effective mobilities of the carriers in the near surface space, the so-called surface mobilities of the holes μ_p and electrons μ_n [3] instead of their volumetric values (μ_{nb}, μ_{pb}).

$$\mu_n = \frac{\mu_{nb}}{1 + k_d \mu_{nb} \sqrt{\frac{m_n^* n_i}{\varepsilon_s \varepsilon_0}} - \frac{\sqrt{1 + |u_s - u_b|}}{u_s - u_b} F(u_s, u_b)}, \tag{8}$$

$$\mu_p = \frac{\mu_{pb}}{1 + k_d \mu_{pb} \sqrt{\frac{m_p^* n}{\varepsilon_s \varepsilon}} \frac{\sqrt{1 + |u_s - u_b|}}{u_s - u_b} F(u_s, u_b)} . \tag{9}$$

The coefficient of diffusive dispersion of the carriers define the degree of diffusivity of charge carriers reflections from the semiconductors surface. It is included in the interval 0 and 1. For $k_d = 0$ the reflections are a mirror image, for $k_d = 1$ they are clearly diffusive.

3. The longitudinal acoustoelectric method — The experimental results

Using a simplified physical model of this phenomenon, one can assume that longitudinal acoustoelectric current I_{AE} flows in a surface layer which thickness equals to the effective Debye length L. If a sample has finite dimensions, then in its remaining volume a current j_k flows which compensates the acoustoelectric current I_{AE}.

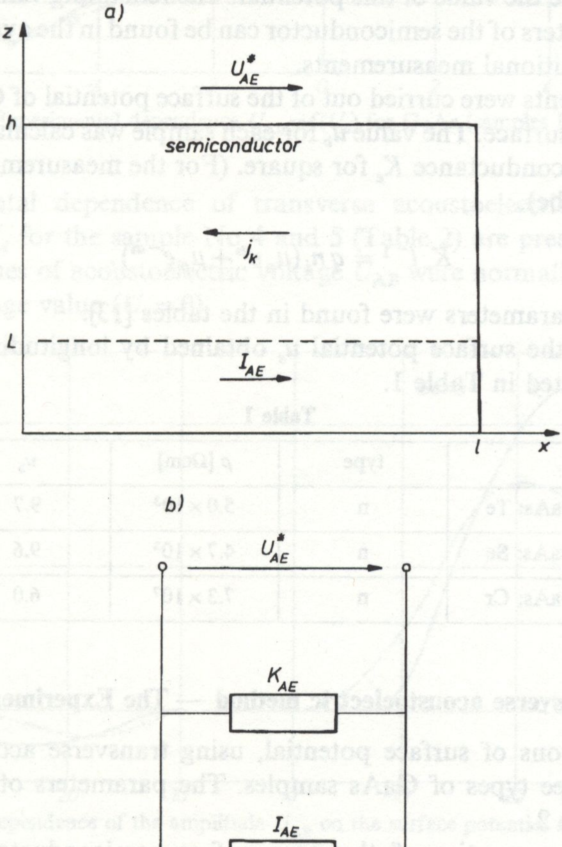

Fig. 2. a) Model of longitudinal acoustoelectric effect, b) Substitute scheme for the model longitudinal acoustoelectric effect.

If U^{*}_{AE} is the longitudinal acoustoelectric voltage, one can define a new quantity — the acoustoelectric conductance of the semiconductor K_{AE} [4]:

$$U^{*}_{AE} \cdot K_{AE} = I_{AE}. \tag{10}$$

K_{AE} is the conductance of a sample of thickness l. The values of the "usual" conductance of sample K_e and the acoustoelectric conductance K_{AE} depends on the bulk and surface properties of semiconductor. After appropriate calculations [3]:

$$\frac{(K_e - K_{AE})\, l}{b\, q} = \mu_p\,(n_i L_i G_i + p_b L) + \mu_n\,(n_i L_i G_n + n_b L). \tag{11}$$

All the terms in the right side of the equation (4) are only the function of the surface potential u_s of this semiconductor surface which is in contact with wave guide.

The calculation of the difference of the conductance K_e and the conductance K_{AE} allows to define the value of this potential. The remaining value which determine volumetric parameters of the semiconductor can be found in the available literature or obtained from additional measurements.

The measurements were curried out of the surface potential of GaAs samples with a different doping surface. The value u_b for each sample was calculated on the basic of the measurements conductance K_e for square. (For the measurement K_e one can use the four-blade probe).

$$K_e\, l^{-1} = q\, n_i\,(\mu_n e^{u_b} + \mu_p e^{-u_b}). \tag{12}$$

The other GaAs parameters were found in the tables [13].

The values of the surface potential u_s obtained by longitudinal acoustoelectric method are presented in Table 1.

Table 1

No		type	ρ [Ωcm]	u_b	u_s
1	GaAs: Te	n	5.0×10^3	9.7	$-11{,}4$
2	GaAs: Se	n	4.7×10^3	9.6	-11
3	GaAs: Cr	n	7.3×10^7	6.0	-14

4. The transverse acoustoelectric method — The Experimental Results

The investigations of surface potential, using transverse acoustoelectric effect, were done for three types of GaAs samples. The parameters of these samples are presented in Table 2.

The electrical properties of the near-surface semiconductor region one can changed by applying an external perpendicular voltage U_d across the semiconductor sample. The amplitude U_{AE} of TAV, the shape of the TAV impulse and even the sign of the TAV are dependent an external voltage U_d.

The values of the bulk electrical parameters GaAs samples, which were need for theoretical analysis one can found in tables [13].

The experiments have been performed using the experimental setup described in the paper [5].

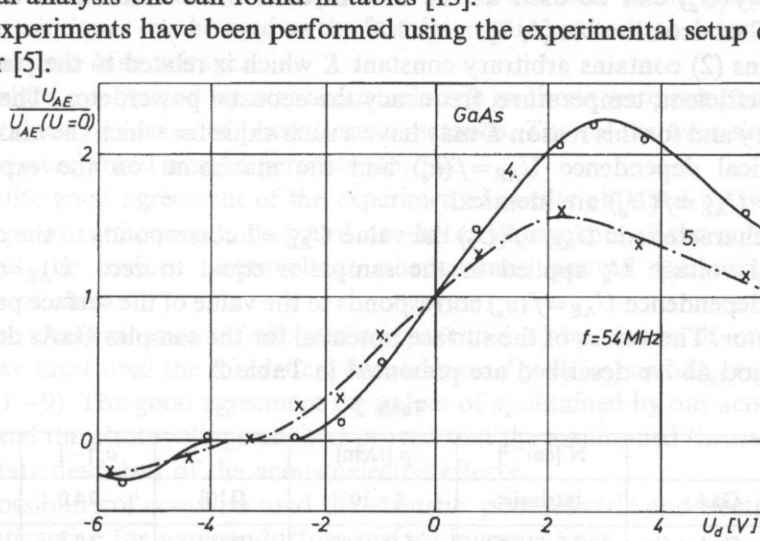

Fig. 3. Experimental dependence $U_{AE}=f(U_d)$ for GaAs (samples No 4, 5).

The experimental dependence of transverse acoustoelectric voltage U_{AE} on external voltage U_d for the sample No 4 and 5 (Table 2) are presented on Fig. 3.

The above values of acoustoelectric voltage U_{AE} were normalized for the case of zero external voltage value ($U_d=0$).

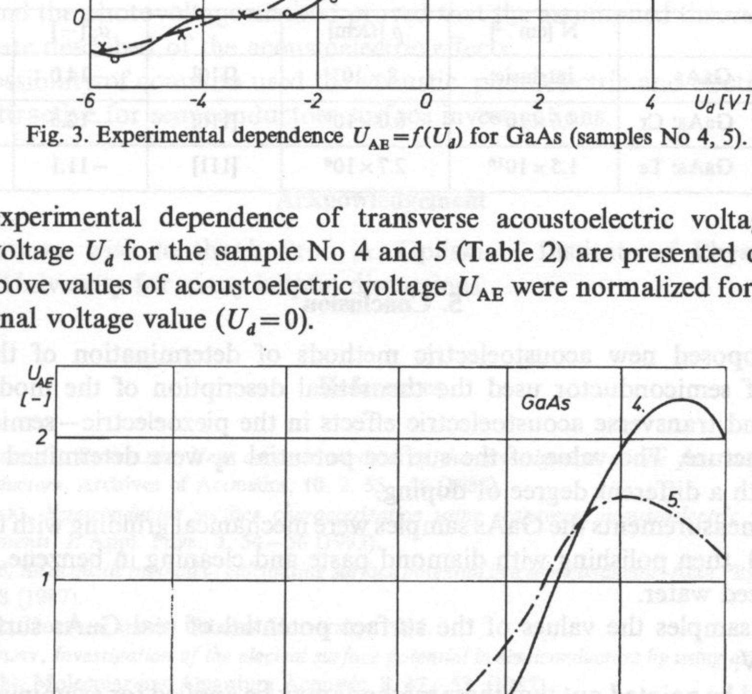

Fig. 4. Theoretical dependence of the amplitude U_{AE} on the surface potential u_s (samples No 4, 5).

The theoretical dependence of the amplitude U_{AE} on the surface potential may be obtained numerically using Eq. (2) and (3). In Fig. 4 the theoretical dependence $U_{AE}=f(u_s)$ for the sample No 4 and 5 are presented.

The comparison between experimental dependence $U_{AE}=f(U_d)$ and theoretical curve $U_{AE}=f(U_d)$ can be used as the new method of determination the surface potential of semiconductors [6, 7].

Equations (2) contains arbitrary constant K which is related to the piezoelectric coupling coefficient, temperature, frequency the acoustic power, etc... The constant K is arbitrary and for this reason K may have a such value for which the maximum on the theoretical dependence $U_{AE}=f(u_s)$ and the maximum on the experimental dependence $U_{AE}=f(U_d)$ are identical.

On the characteristic $U_{AE}=f(U_d)$ the value $U_{AE}=1$ corresponds to the case when the external voltage U_d applied to the sample is equal to zero. $U_{AE}=1$ on the theoretical dependence $U_{AE}=f(u_s)$ corresponds to the value of the surface potential in semiconductor. The values of the surface potential for the samples GaAs determined by the method above described are presented in Table 2.

Table 2

No		N [cm^{-3}]	ρ [Ωcm]		u_s [−]	$q\phi_s$ [eV]
4	GaAs	intrinsic	8×10^7	[110]	−14.0	0.44
5	GaAs: Cr	8.6×10^{15}	6.0×10^6	[110]	−12.5	0.40
6	GaAs: Te	1.5×10^{16}	2.7×10^6	[111]	−11.1	0.37

5. Conclusion

The proposed new acoustoelectric methods of determination of the surface potential of semiconductor used the theoretical description of the model of longitudinal and transverse acoustoelectric effects in the piezoelectric–semiconductor layered structure. The value of the surface potential u_s were determined for GaAs samples with a different degree of doping.

Before measurements the GaAs samples were mechanical grinding with the corund powder 600. then polishing with diamond paste and cleaning in benzene, methanol and deionized water.

For all samples the values of the surface potential of real GaAs surfaces were nearly 0.4 V.

It should be pointed out that these methods may be applied for examining mean of high resistance samples. For low-resistance samples, where the concentration of carries are great, the effective Debye length are small. The interaction between SAW and carriers in semiconductor are weak and amplitudes of the acoustoelectric current and traverse acoustoelectric voltage are small. For these cases the accuracy δu_s of the surface potential determination is small. But for low-resistance semiconductors the non acoustic methods of the surface potential determination give results with great errors, too.

It should be pointed out that the presented here acoustoelectric methods are nondestructive ones and give the possibility to determine of the values of the surface semiconductor parameters in hight frequency range. Moreover, the transverse acoustoelectric method does not require the ohmic contacts to the sample.

These techniques can be used as the fast diagnostic methods to detect the surface potential at zero bias voltage.

The values u_s obtained by new acoustoelectric methods were compared with the values obtained by means of photoelectric methods. The results were similar — the differences were about several percents [15, 16].

The quite good agreement of the experimental results obtained by two independent groups of surface methods based on the measurements of the acoustoelectric effects and the surface photovoltage phenomenon proved the complementary characters of ones.

For the determination of the surface potential u_s by means of our acoustics methods we must used the theoretical dependences $I_{AE}=f(u_s)$ and $U_{AE}=f(u_s)$ (ch. 2, formulae 1–9). The good agreement the values of u_s obtained by our acoustoelectric methods and the photovoltage method proved that the assumoned theoretical model in good state described of the acoustoelectric effects.

The possibility of common used the acoustic, photoelectric and electric methods are very attractive for semiconductors surface investigations.

Acknowledgement

The authors wish to thank Prof. A. Opilski of Institute of Physics Silesian Technical University for many helpful discussions.

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Received December 30, 1992, revised version August 21, 1993