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AN ACOUSTIC METHOD OF CALCULATING THE SURFACE POTENTIAL IN A SEMICONDUCTOR[1)]

KUBIK, Z.,[2)], OPILSKI, A.,[2)] Gliwice

The method in question utilizes the mutual iteraction of the mechanical and the electrical fields in the so-called acousto-electric layer structure.

The structure consists of tightly adhering semiconductor plate and a piezoelectric plate. On the surface of the piezoelectric there propagates a surface elastic wave. As the penetration depth of the electric field of the surface wave is identical with the interaction range of the surface states of the semiconductor, the value of the acousto-electric current depends upon the value of the electric fields, the source of which is the electric charge on the surface of the semiconductor.

The value of the so-called surface potential of the semiconductor can be defined by an appropriate measurements.

I. INTRODUCTION

In recent years a rapid development of acoustic methods for the investigation of solids has been observed. The main advantages of these methods are a quick and non-destructive measurement and above all the possibility of carrying out measurement for a wide range of frequency. Acoustic methods help to obtain information about the mechanical qualities, the crystal structure, the electrical, optical and magnetic qualities of solids. We can apply an acoustic method, for example, to determine the activation energy of charge carries, their mobility and parameters of state doping.

The semiconductor surface may be examined by methods based on the use of surface acoustic waves. The most important of them is the method which utilizes surface wave propagation in the piezoelectric-semiconductor layer structure. Due to it the parameters of quick surface states can be determined: velocity of surface trapping, effective life time of free charge carriers in traps, state concentration (from the measurement of the surface wave attenuation [1]). The

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[2)] Department of Physics, Silesian Technical University, Krzywoustego 2, 44—100 GLIWICE, Poland

measurement of the longitudinal acoustoelectric effect allows to examine the relaxation of slow surface states [2].

There is presented the method of the surface potential determination of a semiconductor applying the measurement of the longitudinal acoustoelectric effect in the piezoelectric-semiconductor layer structure. In such a structure a piezoelectric is the surface wave carrier. The semiconductor plate touches the piezoelectric surface on the side where the wave propagates.

II. THE LONGITUDINAL ACOUSTOELECTRIC EFFECT IN THE LAYER STRUCTURE TAKING INTO ACCOUNT THE SURFACE POTENTIAL IN A SEMICONDUCTOR

The electric field of the surface wave penetrates a semiconductor and induces excess carriers in it. The same field cause their drift. The electric field as well as the excess concentration are wave functions. The mean of their product is not zero of course. As a result direct current appears. One of them propagates in the direction of the surface wave, the other one is perpendicular to the semiconductor surface. In the time which equals Maxwell's relaxation time the current which is lateral to the surface becomes compensated in the time diffusion current related to the new unbalanced charge distribution. It is connected with the appearance of potential difference between a semiconductor surface and its inside. These two phenomena are called acoustoelectric effects one of them is the longitudinal acoustoelectric effect, the other is the lateral acoustoelectric effect.

If the interaction in the layer structure is small, the quantity of these phenomena may be calculated applying the results of the linear theory as well as the flat bonds approximation [3].

The calculated value of the longitudinal acoustoelectric current I_{AK} is determined by the following equation

$$I_{AK} = \frac{\mu_p^2 p_b - \mu_n^2 n_b + n_i \dfrac{L_i}{L_e}(\mu_p^2 G_p - \mu_n^2 G_n)}{\mu_p p_b + \mu_n n_b + n_i \dfrac{L_i}{L_e}(\mu_p G_p + \mu_n G_n)} \frac{2\alpha_0 S}{V_0} b \qquad (1)$$

where

$$\alpha_0 = \frac{K_e^2}{2V_0}\varepsilon_p\varepsilon_0 \frac{\omega^2 q\left[\mu_n n_b + \mu_p p_b + n_i \dfrac{L_i}{L_e}(\mu_n G_n + \mu_p G_p)\right]}{\varepsilon_0^2(\varepsilon_s + \varepsilon_p)^2\omega^2 + q^2\left[\mu_n n_b + \mu_p p_b + n_i \dfrac{L_i}{L_e}(\mu_n G_n + \mu_p G_p)\right]^2} \qquad (2)$$

$$G_p = \int_{u_s}^{u_b} \frac{e^{-u} - e^{-u_b}}{F(u, u_b)} du \qquad G_n = \int_{u_s}^{u_b} \frac{e^{u} - e^{u_b}}{F(u, u_b)} du \qquad (3)$$

$$F(u, u_b) = \pm\sqrt{2}[(u - u_b)\sinh u_b - (\cosh u_b - \cosh u)]^{1/2} \qquad (4)$$

$$u = \frac{q\varphi}{k_B T} \qquad u_s = \frac{q\varphi_s}{k_B T} \qquad u_b = \frac{q\varphi_b}{k_B T} \qquad (5)$$

μ_n, μ_p are electron and hole mobilities, $p_b = n_i \exp\{-u_b\}$; $n_b = n_i^2/p_b$ are electron and hole concentration inside the semiconductor, n_i is electron concentration in the intrinsic semiconductor L_i, L_e are intrinsic and effective Debye lengths, G_n, G_p are — Kingston functions of the second type, $F(u, u_b)$ is a Kingston function of the first type, α_0 is the electron surface wave attenuation coefficient, v_0 is surface wave velocity, b is width of the semiconductor plate, K_e is effective electromechanical coupling coefficients, ε_p, ε_s are dielectric constants of the piezoelectric and semiconductor, ω is wave circular frequency, q is electron charge, φ_s, φ_b is electric potential on the semiconductor surface (surface potential) and inside it, u_s is non-dimensional surface potential.

For specifying the above expressions there can be introduced instead of the volumetric mobilities (μ_n, μ_p) the effective mobilities of the carriers in the near surface space, the so-called surface mobilities of the holes μ_{ps} and electrons μ_{ns} [4],

$$\mu_{ns} = \frac{\mu_n}{1 + k_d\mu_n\sqrt{\dfrac{m_n^* n_i}{\varepsilon_s\varepsilon_0}}\dfrac{\sqrt{1 + |u_s - u_b|}}{u_s - u_b}F(u_s, u_b)} \qquad (6)$$

$$\mu_{ps} = \frac{\mu_p}{1 + k_d\mu_p\sqrt{\dfrac{m_p^* n_i}{\varepsilon_s\varepsilon_0}}\dfrac{\sqrt{1 + |u_s - u_b|}}{u_s - u_b}F(u_s, u_b)} \qquad (7)$$

k_d is coefficient of diffusive dispersion of charge carriers on the semiconductor surface, m_p^*, m_n^* is effective mass of holes and electrons.

The coefficient of diffusive dispersion of the carriers defines the degree of diffusivity of charge carriers reflections from the semiconductor surface and 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. The quanitty of the coefficient is not known beforehand therefore the calculations are made for the extreme values.

In the simplified model of the longitudinal acoustoelectric effect it is assumed that the current I_{AK} flows in the near-surface space whose thickness is equal to the extrinsic Debye length L_e. In the semi-infished semiconductor other currents do not appear. In the real case the sample has finite dimensions so that its length l is much bigger than its thickness h (it allows not to take into account disturbances at the ends of the sample) inside the semiconductor there must appear the compensated current (fig. 1). It may be assumed that it flows in the limited space $L_e < x_3 < h$.

If the substitute scheme for the model of this effect is introduced as in fig. 2, a certain relation takes place

$$U_{AK}K_{AK} = I_{AK} \tag{8}$$

K_{AK} is acoustoelectric conductance.

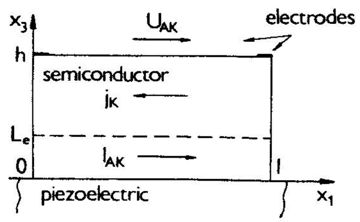

Fig. 1. Simple model of longitudinal acoustoelectric effect.

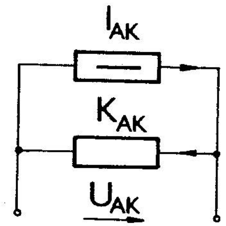

Fig. 2. Substitute scheme for the model of longitudinal acoustoelectric effect.

III. ACOUSTOELECTRIC CONDUCTANCE

The value of the acoustoelectric conductance K_{AK} depends on the volumetric equalities of the semiconductor and the surface state which does not touch the piezoelectric. The Kirchoff law must be applied to calculate it

$$b\int_{L_e}^{h} j_k(x_3)\,\mathrm{d}x_3 = I_{AK} \tag{9}$$

$$l\frac{j_k(x_3)}{\sigma(x_3)} = U_{AK} \qquad x_3 > L_e \tag{10}$$

σ the sample conductivity.
Hence,

$$K_{AK} = \frac{b}{l}\int_{L_e}^{h} \sigma(x_3)\,\mathrm{d}x_3\,. \tag{11}$$

Taking into consideration the charge carrier diffusion on the surface which does not touch the piezoelectric ($x_3 = h$) it should be assumed that on the limit $x_3 = h - L_e'$ (the index prime will denote these physical quantities whose value is connected with the state of the surface not touching the piezoelectric) there takes place the jump change of the mobility:

$$\text{for } L_e < x_3 < h - L_e' \qquad \sigma(x_3) = q(\mu_n n_b + \mu_p p_b) = \sigma_b \tag{12}$$

$$\text{for } h - L_e' < x_3 < h \qquad \sigma(x_3) = q\,[\mu_{ns}' n'(x_3) + \mu_{ps}' p'(x_3)] \tag{13}$$

$n' = n_i e^{u'}$, $p' = n_i e^{-u'}$ are electron and hole concentrations in the near surface space.
Hence, having taken into account this assumption the result is

$$K_{AK} = \frac{b}{l}\left[(h - L_e - L_e')\,\sigma_b + q\int_{h-L_e'}^{h} (\mu_{ns}' n' + \mu_{ps}' p')\,\mathrm{d}x_3\right]. \tag{14}$$

The integral in equation (14) can be calculated using the relations in the formulas (3, 4, 5). Finally

$$K_{AK} = \frac{b}{l}[\Delta\sigma_\square' + (h - L_e - L_e')\,\sigma_b + q(\mu_{ns}' n_b + \mu_{ps}' p_b)\,L_e'] \tag{15}$$

$$\Delta\sigma_\square' = qn_iL_i(\mu_{ns}' G_n' + \mu_{ps}' G_p') \tag{16}$$

$\Delta\sigma_\square'$ is the change in the surface sheet conductance of the surface $x_3 = h$.

IV. ELECTRIC CONDUCTANCE OF A SEMICONDUCTOR

The value of the electric conductance of the whole sample may be calculated in a similar way

$$K = \frac{b}{l}\int_{0}^{h} \sigma(x_3)\,\mathrm{d}x_3\,. \tag{17}$$

It should be assumed that the carrier mobility changes in the jump-like way on the limit $x_3 = h - L_e'$ as well as on the limit $x_3 = L_e$

$$\text{for } 0 < x_3 < L_e \qquad \sigma(x_3) = q\,[\mu_{ns} n(x_3) + \mu_{ps} p(x_3)]$$

n, p are electron and hole concentrations in the near-surface space.
Hence:

$$K = \frac{b}{l}\left[(h - L_e' - L_e)\,\sigma_b + q\int_{0}^{L_e} (\mu_{ns} n + p\mu_{ps})\,\mathrm{d}x_3 + q\int_{h-L_e'}^{h} (\mu_{ns}' n' + \mu_{ps}' p')\,\mathrm{d}x_3\right]. \tag{18}$$

Having applied relations (3, 4, 5) the final result is

$$K = \frac{b}{l}\Big[(h - L_e - L_e')\,\sigma_b + \Delta\sigma_\square + \Delta\sigma_\square' + q(\mu_{ns} n_b + \mu_{ps} p_b)\,L_e + $$
$$+ q(\mu_{ns}' n_b + \mu_{ps}' p_b)\,L_e'\Big] \tag{19}$$

$$\Delta\sigma_\square = qn_iL_i(\mu_{ns} G_n + \mu_{ps} G_p)\,. \tag{20}$$

V. DETERMINATION OF SURFACE POTENTIAL U_s

After side subtraction of the equations (15, 19) and simple substitution the result is as follows

$$\frac{(K - K_{AK})\, l}{bq} = \mu_{ps}(n_i L_i G_p + L_e p_b) + \mu_{ns}(n_i L_i G_n + L_e n_b). \qquad (21)$$

All the terms on the right-hand side of the equation are only the function of the surface potential u_s of one of the semiconductor surfaces (it touches the piezoelectric). Calculating the value difference of the conductance K and the conductance K_{AK} allows to define the value of this potential. The remaining values which determine volumetric parameters of the given semiconductor may be found in the tables or defined from additional mesurement.

VI. METER CIRCUIT

The determination of the acoustic conductance K_{AK} requires the use of the surface wave of constant power and frequency (the condition of the direct current I_{AK} at the time of measurement). There was used the circuit which utilizes a surface progressive wave (fig. 3).

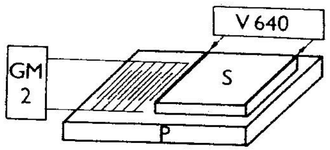

Fig. 3. Meter circuit of longitudinal acoustoelectric effect.

This meter circuit is characterized by the simplicity of its construction, a high sensitivity, and small measuring errors. The signal from the power generator GM-2 is transmitted to the interdigital transducer. The current I_{AK} or voltage U_{AK} are measured by the multimeter V-640. The inner resistance of the ammeter multimeter was always much smaller than the acoustoelectric resistance (K_{AK}^{-1}) in each of the measured semiconductor samples, the measured current was equal to the current I_{AK} (practically the shortened ends of the sample). The inner resistance of the voltmeter was much greater than the acoustoelectric resistance.

The measurement of conductance K was carried out in the typical circuit with the precisely measured current. The current was measured by the multimeter V-640, the voltage by the same multimeter or by the digital voltmeter U 722 K. For measuring the conductance K the same electrodes and leads were used as those applied in the K_{AK} measurements.

VII. RESULTS OF MEASUREMENT

Measurements were carried out of the surface potential of silicon samples with a different degree of doping and unequal surfaces. The value u_b was calculated on the basis of the known resistance for the square $R_\square$ of the given sample (for the measurement there was used the four-blade probe)

$$(R_\square h)^{-1} = q n_i (\mu_n e^{u_b} + \mu_p e^{-u_b}). \qquad (22)$$

The other silicon parameters were found in the tables.

For the wave-quick background $LiNbO_3$ was used, which had the X cutting and the propagation direction Z.

These tested samples were pressed down to the waveguide by means of elastic contacts which simultaneously secured the electric contact with electrodes at the ends of the samples evaporated in a vacuum. The measurements were performed at the frequency 17.3 MHz.

The measurement of the voltage U_{AK} and the current I_{AK} was carried out for different powers of the surface wave. The conductance K_{AK} was determined using the Gauss equalizing method from the series of such measurements. The conductance K was also defined from the series of measurements.

The surface potential was calculated, finally, on the basis of equation (21) assuming that the value k_d equals zero or one. Because of the integrals G_n, G_p these calculations were carried out numerically.

In table 1 there are data of the given samples (the kind of surface treatment, type of conductivity, specific resistance) and there are given the calculate values of the surface potentials for $k_d = 0$ and $k_d = 1$. For four low-resistance samples (nr 11—14) the value u_s for $k_d = 1$ was not given because of the high measuring error (the value u_s has no physical sense).

As it can be noticed from the data in the table in every case there was stated the accumulation layer of the space charge ($|u_s| > |u_b|$). The potential difference ($u_s - u_b$) is usually bigger for a more demaged surface, it is clearly obvious for voltages u_s calculated for $k_d = 1$. The increment of Q ($Q = u_s(k_d = 1) - u_s(k_d = 0)$), denoting the quantity of the systematic error, is connected with the lack of knowledge of the real value k_d and is greater for high-doped silicon samples.

Taking into account the complicated dependence of the surface potential on the measured quantities, the error which was the result of the in accuracy of determination of K and K_{AK} was calculated numerically.

In table 2 the values of the absolute error Δu_s and of the relative error δu_s, connected with the accuracy of measurements, are presented, as well as the increment Q.

Table 1

nr	surfacing	type	$\varrho(\Omega\,\text{cm})$	u_s		u_b
				$k_d = 0$	$k_d = 1$	
1	polishing	n	68000	6.83	6.88	1.15
2	polishing	n	68000	2.46	2.47	1.15
3	polishing	p	16000	−10.56	−10.63	−3.66
4	polishing	p	4310	−11.83	−11.98	−4.98
5	polishing	p	2200	−12.93	−13.18	−5.65
6	polishing	p	2200	−12.28	−12.47	−5.65
7	grinding	n	48.4	13.32	15.19	8.44
8	grinding	n	32.1	13.36	15.37	8.85
9	grinding	n	30.1	12.54	13.86	8.91
10	grinding	n	17.7	15.32	26.55	9.44
11	grinding	n	3.8	23.14		10.98
12	grinding	n	3.8	25.45		10.98
13	grinding	n	3.8	25.49		10.98
14	grinding	n	0.743	26.47		12.61

Table 2

nr	$k_d = 0$		$k_d = 1$		Q
	Δu_s	δu_s %	Δu_s	δu_s %	
1	0.08	1.20	0.09	1.26	0.05
2	0.03	1.36	0.04	1.38	0.01
3	0.15	1.42	0.15	1.42	0.08
4	0.11	0.95	0.12	0.99	0.15
5	0.13	0.98	0.14	1.09	0.24
6	0.17	1.41	0.19	1.48	0.19
7	1.07	8.04	1.86	12.26	1.87
8	0.69	5.13	1.31	8.50	2.01
9	1.10	9.02	1.70	12.21	1.32
10	2.82	18.39	12.70	47.84	11.20

In the case of the samples 11 to 14 the value of the error was over 100 %. The results obtained were given because they determine the parameters of silicon samples, which should not be investigated applying a used meter circuit.

It should be stated that: the error of determining the potential δu_s is greater when it is assumed that $k_d = 1$, the difference is minimal for high-resistivity samples and it distinctly grows with the increase of doping. The error δu_s is small for high-resistance samples and significant for low-resistance samples, the increment Q can be compared to the error Δu_s.

The main cause of the high error for low-resistivity samples is a too low frequency of the surface wave in the given meter circuit. As far as the relaxation dependence of the acoustoelectric effect on the frequency is concerned, the value of the measured current I_{AK} could, in this case, be compared to the value of the error of the given meter. The increase of the generator work frequency was connected with the decrease of the output power. As a result an increase of the value of the measured current was not obtained.

VIII. CONCLUSION

The proposed acoustoelectric method of determining the surface potential of a semiconductor was worked out on the basis of the theoretical description of the simplified model of the longitudinal acoustoelectric effect in the piezoelectric-semiconductor layer structure.

The constructed meter circuit was easily maintained, very sensitive and caused small measuring errors.

The value of the surface potential u_s was determined for silicon samples with a different degree of doping. The quality of the errors was calculated.

It can be stated that this method may be applied for examining mean and high resistance samples because in those cases the systematic error of the method is small. Its measure is the value of the increment Q. The error δu_s is also small. The low-resistance samples should not be investigated by this method because even if the value of the error δu_s, were minimized, the systematic error of the method would be quite significant.

The method can also be applied to the simple examination of the semiconductor surface used for the construction of acoustoelectric layer circuits.

The method can be used with the most common photoelectric methods and those based on the field effect.

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ОБ ОДНОМ АКУСТИЧЕСКОМ МЕТОДЕ РАСЧЕТА ПОВЕРХНОСТНОГО ПОТЕНЦИАЛА В ПОЛУПРОВОДНИКЕ

Рассмотренный метод состоит в использовании взаимодействия механических и электрических полей в так называемой акустоэлектрической слоистой структуре. В состав структуры входят тесно прижатые друг к другу полупроводниковая и пъезоэлектрическая плиты, причем на поверхности пъезоэлектрика распространяется поверхностная волна упругой деформации. Поскольку глубина проникновения электрического поля поверхностной волны в слой совпадает с радиусом взаимодействия поверхностных состояний в полупроводнике, величина акусто-электрическиго тока зависит от величины электричских полей, источником которых служит электрический заряд на поверхности полупроводника. Величина так называемого поверхностного потенциалла полупроводника может быть определена при помощи соответствующих измерений.