

# Determination of Some Kinetic Parameters of Fast Surface States in Silicon Single Crystals by Means of Surface Acoustic Wave Method

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The paper presents the acoustic method for determining some parameters of fast surface states in semiconductors. This method uses the interactions of the phonon–electron type for determining both the effective carrier lifetime  $\tau$  influenced by the fast surface energetic states and the velocity  $g$  of the carrier trapped by the surface states. Some experimental results of the parameters  $\tau$  and  $g$  in near-surface region of real Si(111) samples for their various surface treatments, obtained by the offered method, are presented.

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## 1. Introduction

Among the methods of investigations of semiconductor surfaces, there are no methods of investigating the kinetic properties of electrical carriers in fast and very fast surface states [1]. The existing methods allow only investigations of the surface states with a carrier lifetime  $\tau$  of above  $10^{-8}$  s [1–3]. In the case of extrinsic semiconductors the surface states may, however, be considerably faster (the carrier lifetime in surface traps is usually smaller than  $10^{-8}$  s). In such cases the existing methods of determining the parameters of fast surface states allow only to estimate these parameters, since the obtained results exhibit a considerable uncertainty. For this reason, investigations of the kinetic properties of fast surface states are not popular and there are not any new results concerning their determination.

For some years attention has been paid to the influence of the physical state of the near-surface region of a semiconductor on the results of investigations of the acoustoelectric effects in piezoelectric–semiconductor systems [3–9]. Also recently

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attention has been paid to the possibility of applying Rayleigh's surface acoustic waves (SAWs) for investigations of various parameters of solid states [10–14].

In our previous papers [15–17] the theoretical and experimental results of the application of acoustoelectric effects (longitudinal and transverse) for the determination of carrier properties in near-surface region (e.g. the surface electrical potential, carrier concentration, electrical conductivities. . .) have been presented. Problems connected with the determination of the chemical and mechanical means of surface treatments in the first step of preparation of semiconductor plates for technology on their kinetic properties have not often been taken up. The quantitative data concerning the effective lifetime  $\tau$  and the velocity of carrier trapping  $g$  are very seldom presented.

## 2. Some aspects of the interactions of SAW with electrical carriers in near-surface region in semiconductors

The presented method is based on the phenomena of SAW propagation in a system: piezoelectric waveguide–semiconductor structure. The electric field, which accompanies a surface wave in piezoelectric waveguide, penetrates the semiconductor to a depth equal to Debye's screening length [3–5]. Thus, the wave and carriers interaction will be manifested in the semiconductor in the form of acoustoelectric effects [4, 12] and in the piezoelectric waveguide — by an additional attenuation coefficient (the so-called electron attenuation) and by changing the velocity of the acoustic wave [6]. In Fig. 1 the scheme of the system: piezoelectric waveguide–semiconductor is presented.

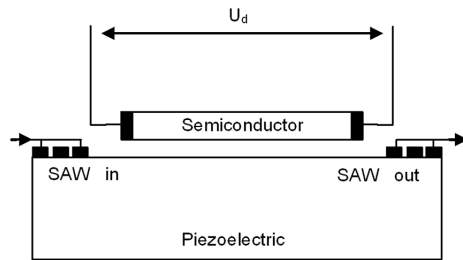


Fig. 1. The idea of the piezoelectric waveguide–semiconductor system for investigation of the near-surface region in semiconductors.

Let us consider the surface wave which propagates on a piezoelectric waveguide. In the same direction the external electric drift field is applied to the semiconductor. The electron coefficient of the attenuation of the surface wave in such a system may be presented by the formula [5, 7]:

$$\alpha_e = \frac{\eta \frac{\epsilon_1}{\epsilon_2} \frac{\omega}{\omega_c} (\gamma + a) \left[ 1 + \frac{\gamma + a}{A_D \frac{\omega}{\omega_c} [(\gamma + a)^2 + b^2]} \right]}{\left[ 1 + \frac{\omega}{\omega_c} \left( 1 + \frac{\epsilon_1}{\epsilon_2} \right) b \right]^2 + \left[ (\gamma + a) \left( 1 + \frac{\epsilon_1}{\epsilon_2} \right) \frac{\omega}{\omega_c} b \right]^2} H, \quad (1)$$

where

$$a = \frac{g}{\nu_w} \frac{\omega \tau}{(\omega \tau)^2}, \quad (2)$$

$$\gamma = 1 - \frac{\mu_0 E_d}{\nu_w}, \quad (3)$$

$$A_D = \frac{1 + L_D^2 k^2}{L_D^2 k^2}, \quad (4)$$

$$b = (\omega \tau) a \quad (5)$$

and  $\nu_w$  is the velocity of SAW,  $E_d$  — the electric drift field,  $\mu_0$  — the mobility of electrons in semiconductor,  $L_D$  — the Debye length,  $k$  — the wave number of SAW,  $\omega$  — the angular surface wave frequency,  $\omega_c$  — the so-called “frequency of Maxwell’s conductivity relaxation”,  $\eta$  — the square of the electromechanical coupling coefficient,  $\gamma$  — the drift parameter,  $\epsilon_1$ ,  $\epsilon_2$  — the permittivity of waveguide and semiconductor, respectively,  $g$  — the velocity of carriers trapping into surface states in semiconductor,  $\tau$  — the effective lifetime of electrical carriers in fast surface states,  $H$  — constant, whose value depends on the elastic and piezoelectric properties of the waveguide and investigated semiconductor.

The process of electrical carriers trapping in the surface states in a semiconductor, under the influence of a surface wave which propagates in a piezoelectric crystal, was considered in detail in papers [5, 7]. Figure 2 presents changes of electron attenuation on the external electric field  $E_d$  in the semiconductor.

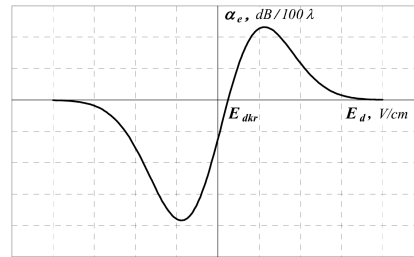


Fig. 2. Electron attenuation  $\alpha_e$  of a surface acoustic wave in the function of an external electric field  $E_d$ .

The critical electrical drift field is a field at which the electron attenuation of the wave is equal to zero

$$\alpha_{cr}(E_{dkr}) = 0. \quad (6)$$

In Ref. [7] it was shown that the equation for the critical drift field has the following form:

$$E_{\text{dkr}} = \frac{\nu_w}{\mu_0} \left[ 1 + \frac{\omega\tau}{1 + (\omega\tau)^2} \right]. \quad (7)$$

Accordingly

$$E_{\text{dkr}}^0 = \frac{\nu_w}{\mu_0}, \quad (8)$$

where  $E_{\text{dkr}}^0$  is the critical drift field for the theoretical case, when no surface states exist in the semiconductor. From Eqs. (7) and (8) it follows that the relative change of the critical drift field, caused by surface states, is given by

$$\frac{E_{\text{dkr}} - E_{\text{dkr}}^0}{E_{\text{dkr}}^0} = \frac{\Delta E_{\text{dkr}}}{E_{\text{dkr}}^0} = \frac{g}{\nu_w} \frac{\omega\tau}{1 + (\omega\tau)^2}. \quad (9)$$

This relation is presented in Fig. 3.

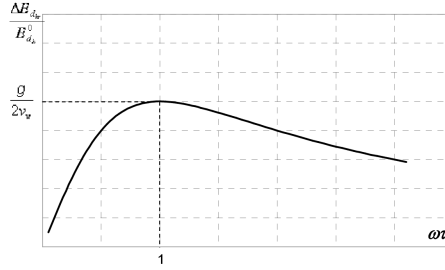


Fig. 3. The characteristics  $\Delta E_{\text{dkr}}/E_{\text{dkr}}^0 = f(\omega\tau)$ .

The idea of assigning the parameters  $\tau$  and  $g$  of surface states consists in the determination of the electron attenuation coefficient as the drift field function for different frequencies of the surface waves. From the characteristics  $\alpha_e = f(E_d)$  one can find  $E_{\text{dkr}}$  for each angular frequency  $\omega$ , next, one can determine the characteristics  $\Delta E_{\text{dkr}}/E_{\text{dkr}}^0 = f(\omega)$  and finally one calculates the carrier lifetime  $\tau$  in the surface states as (Fig. 3)

$$\tau = \frac{1}{\omega}. \quad (10)$$

The velocity of trapping of carriers  $g$  in fast surface states is defined by the relation (Fig. 3):

$$g = 2\nu_w \left( \frac{\Delta E_{\text{dkr}}}{E_{\text{dkr}}^0} \right)_{\text{max}}. \quad (11)$$

Therefore, if the surface wave propagates in the structure of a piezoelectric waveguide–semiconductor, two essential parameters of surface states in a semiconductor can be determined from the measurements of the velocity and attenuation of the SAW.

### 3. Experimental setup

As piezoelectric waveguides the lithium niobate  $\text{LiNbO}_3$  plates (propagation plane  $[Y]$  with the wave propagation direction  $[Z]$ ) were used. The idea of

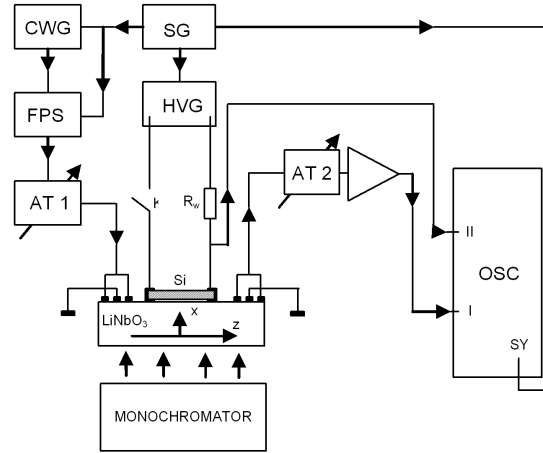


Fig. 4. The scheme of the system for monitoring the electron attenuation coefficient  $\alpha_e$  as a function of the drift field  $E_d$ ; SG — synchronous generator, HVG — high voltage generator, CWG — continuous wave generator, FPS — forming packet system, AT — attenuator, OSC — digital oscilloscope.

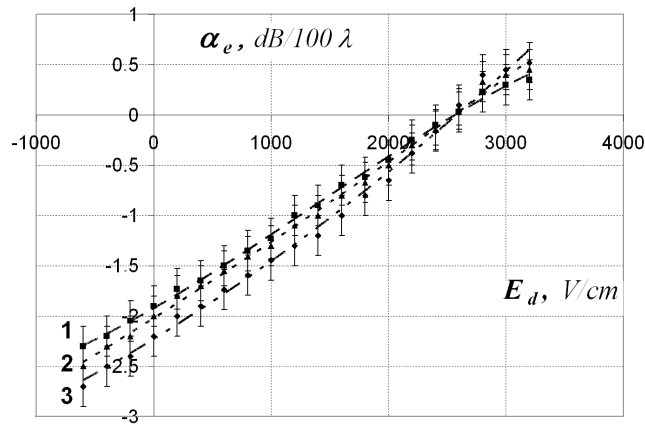


Fig. 5. The experimental characteristics  $\alpha_e = f(E_d)$  for the real surfaces of Si(111) for their various photoconductivities: (1)  $\sigma_1 = 1.2 \Omega \text{ m}^{-1}$ ; (2)  $\sigma_2 = 1.6 \Omega \text{ m}^{-1}$ ; (3)  $\sigma_3 = 1.9 \Omega \text{ m}^{-1}$ .

the experimental setup is presented in Fig. 4. The waveguide system permitted to investigate at the frequency range 2–350 MHz, by using some LiNbO<sub>3</sub> plates with the SAW transducers, made by photolithographic method. Application of a monochromator in the setup permits to illuminate the semiconductor surface and to realize investigations of semiconductor plates for various semiconductor photoconductivities.

Presented here results for the plates of Si with following parameters were obtained: Si[111], *n*-type, electrical conductivity  $\sigma = 1.2 \Omega \text{ m}^{-1}$ , volumetric

mobility of the carrier  $\mu_0 = 0.13 \text{ m}^2/(\text{V s})$ , and the geometrical dimensions  $10 \times 7 \times 0.05 \text{ mm}^3$ .

In Fig. 5 the characteristics of  $\alpha_e = f(E_d)$  for the real Si(111) surfaces after changing their electrical conductivity by means of optical excitations are presented. The measurements were performed for the next photoconductivities of the Si sample:  $\sigma_1 = 1.2 \text{ } \Omega \text{ m}^{-1}$ ;  $\sigma_2 = 1.6 \text{ } \Omega \text{ m}^{-1}$ ;  $\sigma_3 = 1.9 \text{ } \Omega \text{ m}^{-1}$ .

#### 4. The results of investigations of the fast surface state parameters in the Si single crystal samples by means of the SAW method

By means of the above presented method the parameters  $\tau$  and  $g$  for the Si samples were determined whose surfaces were treated in various manner.

Figure 6 presents the characteristics  $\Delta E_{\text{dkr}}/E_{\text{dkr}}^0 = f(\omega\tau)$  of the Si samples, but after their heating in vacuum at a higher temperature ( $\approx 600 \text{ K}$ ) as well as after heating at a higher temperature ( $\approx 600 \text{ K}$ ) but in atmosphere with saturated vapor. On the base of these investigations one can see that the parameters  $\tau$  and  $g$  in Si are essentially different.

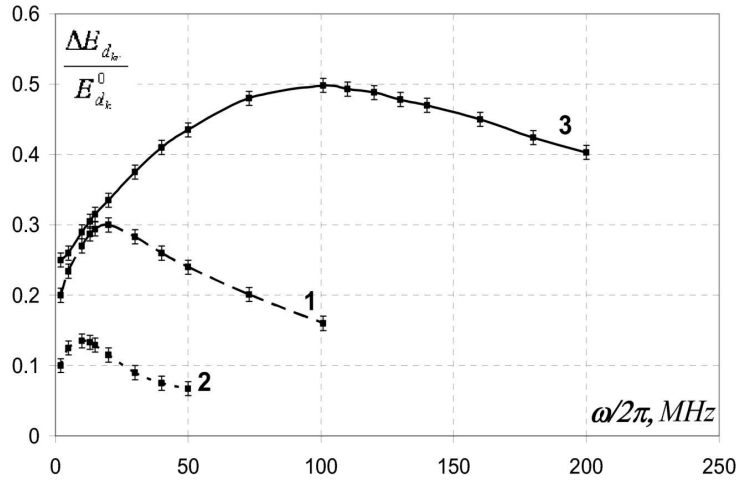


Fig. 6. Relative changes of the critical field  $\Delta E_{\text{dkr}}/E_{\text{dkr}}^0 = f(\omega\tau)$  in Si(111) (1) in vacuum, (2) after heating in vacuum at  $\approx 600 \text{ K}$ , and (3) heating in steam at  $\approx 600 \text{ K}$ .

The results of these investigations are presented in Table. In Table the approximate values of the fast surface states concentrations  $N_t$  are quoted. The procedure of  $N_t$  determination is based on the well known relation [1]:

$$g = S_n V_T N_t, \quad (12)$$

where  $V_T$  is a thermal velocity of electrons in semiconductors and  $S_n$  is an effective cross-section for electron trapping.

For the Si single crystals at room temperature the parameter  $S_n$  is equal approximately to  $\approx 3 \times 10^{-16} \text{ cm}^2$  [1]. Therefore one can estimate the surface

TABLE

Parameters of the fast surface states in Si(111).

| Parameters of Si(111)     | In vacuum                  | After heating<br>in vacuum | After heating<br>in water vapor |
|---------------------------|----------------------------|----------------------------|---------------------------------|
| $\tau$ [s]                | $8.0 \times 10^{-9}$       | $1.6 \times 10^{-8}$       | $1.8 \times 10^{-9}$            |
| $g$ [m/s]                 | 1000                       | 450                        | 3400                            |
| $N_t$ [cm <sup>-2</sup> ] | $\approx 3 \times 10^{13}$ | $\approx 1 \times 10^{13}$ | $\approx 8 \times 10^{13}$      |

concentration  $N_t$  of the fast surface states in tested semiconductors. The concentrations  $N_t$  are of order of  $10^{13}$  cm<sup>-2</sup> and depend strongly on the type of surface treatments.

### 5. Conclusion

The obtained results have shown that the presented acoustic method can be applied to determine the parameters  $\tau$  and  $g$  in investigations of the fast surface states in semiconductors.

The analysis of the method shows that the accuracy of the obtained results is better than 5%, which is a rather good accuracy in the determination of the parameters of fast surface states. It can be pointed out that this method permits dynamic measurements of the surface state parameters over the frequency range up to several hundreds MHz (or even to some GHz), also for different, programmable changed photoconductivity of the tested semiconductors.

Actually, the proposed method is tested in investigations of semiconductors of III–V group. The obtained results will be published.

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