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AN ACOUSTIC METHOD FOR DETERMINING THE PARAMETERS OF FAST SURFACE IN SEMICONDUCTORS STATES

ALEKSANDER OPILSKI, TADEUSZ PUSTELNY

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

The paper presents an acoustic method for determining the parameters of fast surface states in semiconductors. This method uses the interactions of the photon-electron type for determining both the effective carrier life-time τ influenced by the fast surface states and the velocity g of the carrier trapping by surface traps. Some experimental results of the parameters τ and g on a real (111) Si surface, obtained by this method of investigation are presented.

1. Introduction

An ever-growing interest in the physical properties of semiconductor surfaces results both from the influence of the processes, occuring at the surface, on the bulk properties of semiconductors, and from the influence of the physical and chemical surface structure on the operation of semiconductor devices [1, 6, 9, 10, 15].

Among the methods of investigation of semiconductor surfaces, the methods which investigate the energy surface states play an important role [5, 14, 15]. Up to now the existing electrical methods allow only the investigation of surface states with carrier life-times τ of above 10^{-9} s. For extrinsic semiconductors the surface states may, however, be considerably faster (the carrier life-time in surface traps is usually less than 10^{-9} s). In such cases the existing methods for determining the parameters of fast surface states allow us only to estimate these parameters; since the obtained results have the considerable errors. It is the purpose of great interest to search new and more precise investigation methods.

Recently more and more attention has been paid to the possibilities of applying Rayleigh's acoustic surface waves to semiconductor surface investigations [3, 4, 7, 8, 11, 12, 16].

In our previous paper [13], the theoretical basis of a new acoustic method for the investigation of fast surface states in semiconductors has been represented. The method uses the effect of surface wave propagating in a piezoelectric-semiconductor structure for determining both the effective carrier life-time τ influenced by fast surface states and the velocity of carrier trapping, g.

2. The conception of the acoustic method for determining the parameters of fast surface states in semiconductors

A surface wave which propagates on a piezoelectric waveguide surrface, is acompanied by an alternating electric field. If there is a semiconductor over the propagation surface, then the electric wave field penetrates the semiconductor to a depth equal to Debye's screening length [2, 13]. Thus, the values characterizing the wave and carrier interaction will be influenced by the properties of the layer nearest to the semiconductor surface.

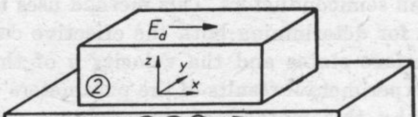

Fig. 1. A diagram of the piezoelectric and semiconductor arrangement (1 – piezoelectric, 2 – semiconductor) used in the experiments

Let us consider the surface wave which propagates in a piezoelectric. In the same direction the external electric drift field is applied to the semiconductor. The electronic coefficient of the damping of the surface wave in such a system

$$a_e = \eta H \frac{\dfrac{\varepsilon_1}{\varepsilon_2}\dfrac{\omega}{\omega_c}(\gamma+a)\left[1+\dfrac{\gamma+a}{\omega/\omega_c[(\gamma+a)^2+b^2]}\right]}{\left[1+\dfrac{\omega}{\omega_c}\left(1+\dfrac{\varepsilon_1}{\varepsilon_2}\right)b^2\right]+\left[(\gamma+a)\left(1+\dfrac{\varepsilon_1}{\varepsilon_2}\dfrac{\omega}{\omega_c}b\right)\right]^2}, \tag{1}$$

where

$$a = \frac{g}{v_f}\frac{\omega\tau}{1+\omega^2\tau^2}, \quad b = \omega\tau a;$$

v_f – the surface wave velocity, g – the velocity of the carrier trapping charge by surface states in a semiconductor, τ – the carrier life – times in surface states, ω — the surface wave frequency, η — the square of the electromechanical feedback coefficient, $\gamma = 1 - \mu_0 E_d / v_f$ — drift parameter, the charge carrier mobility in a semiconductor, μ_0 — the electric field of a drift, ω_c — the so called "frequency of Maxwell's conductivity relaxation", ε_1, ε_2 — the dielectric constants of a piezoelectric and a semiconductor, H — a constant, whose value depends on the elastic and piezoelectric properties of the waveguide and semiconductor.

The electric field which accompanies the surface wave, affects the change in the carrier concentration in the conductivity band, valency band and surface traps. The process of trapping carriers in surface states in a semiconductor, under the influence of a surface wave which propagates in a piezoelectric, was considered in detail in paper [13]. The critical electric drift field is a field at which the attenuation of the wave is equal to zero:

$$a_e(E_{d_{cr}}) = 0. \tag{3}$$

In our previous paper [13], it was shown that the equation for a critical drift field has the following form:

$$E_{d_{cr}} = \frac{v_f}{\mu_0}\left[1 + \frac{g}{v_f}\frac{\omega\tau}{1+\omega^2\tau^2}\right]. \tag{4}$$

Accordingly,

$$E^0_{d_{cr}} = \frac{v_f}{\mu_0}, \tag{5}$$

where $E^0_{d_{cr}}$ is the critical drift field for the theoretical case, where no surface states exists in the semiconductor; from equations (5, 4) it follows that the relative change of the critical drift field, caused by surface states, is given by

$$\frac{E_{d_{cr}} - E^0_{d_{cr}}}{E^0_{d_{cr}}} = \frac{\Delta E_{d_{cr}}}{E^0_{d_{cr}}} = \frac{g}{v_f}\frac{\omega\tau}{1+\omega^2\tau^2}. \tag{6}$$

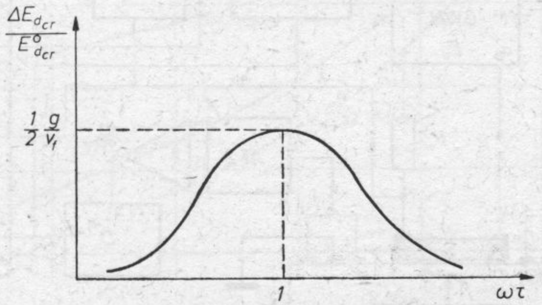

Fig. 2. The characteristics $\frac{\Delta E_{d_{cr}}}{E^0_{d_{cr}}} = f(\omega\tau)$

The idea of determining the parameters τ and g of surface states consists in determining the electric attenuation coefficient as the drift field function for different frequencies of the surface wave. From the characteristics $\alpha_e = f(E_d)$, we can find $E_{d_{cr}}$ for each frequency ω. From the position of the maximum of the characteristics $\Delta E_{d_{cr}}/E_{d_{cr}} = f(\omega)$ at the frequency axis ω, we can determine the carrier life-time τ in surface states as

$$\tau = \frac{1}{\omega_m}. \tag{7}$$

The velocity of trapping is defined by the relation

$$g = 2v_f \left[\frac{\Delta E_{d_{cr}}}{E^0_{d_{cr}}}\right]_{\max}. \tag{8}$$

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

3. Experimental procedure

As a piezoelectric waveguide base, the following monocrystals were used:

— lithium niobate $LiNbO_3$ (propagation plane [Y] with the wave propagation direction [Z];

— bismuth – germanium oxide $BiGeO_{20}$ (propagation plane [111], with the propagation direction [110]).

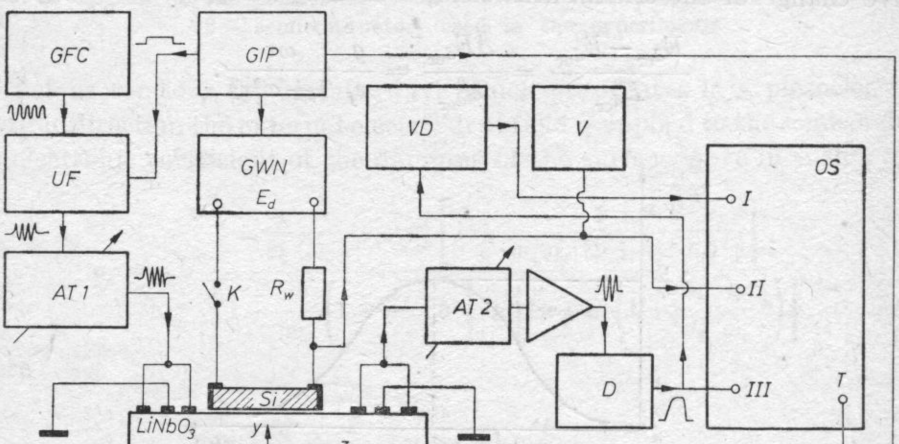

Fig. 3. The system for measuring the electronic attenuation coefficient α_e as a function of the drift field E_d

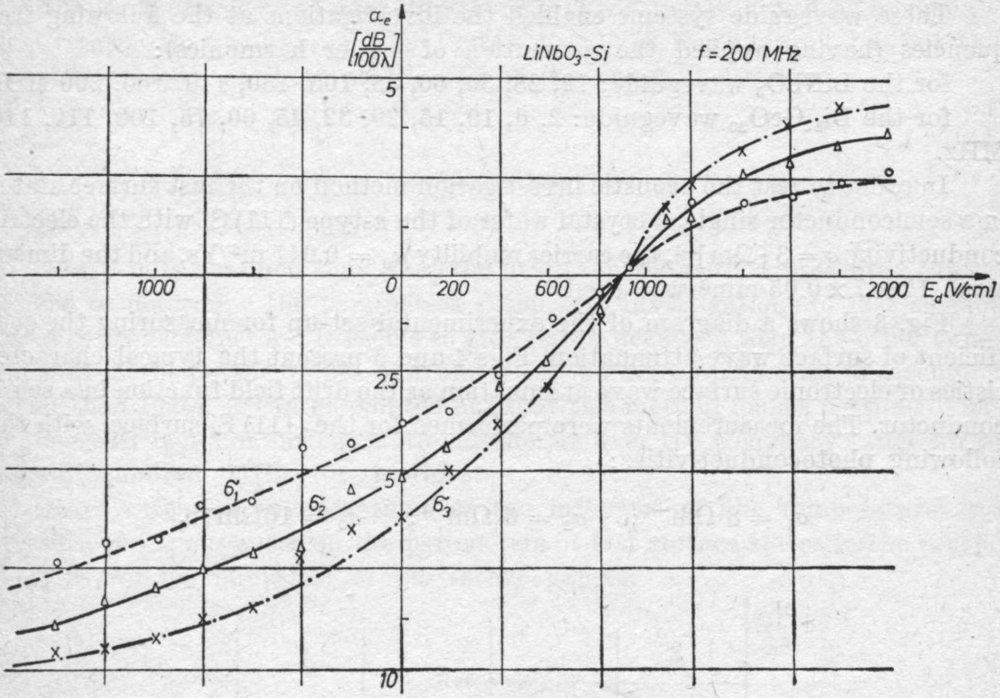

Fig. 4. The electronic attenuation coefficient α_e at 200 MHz

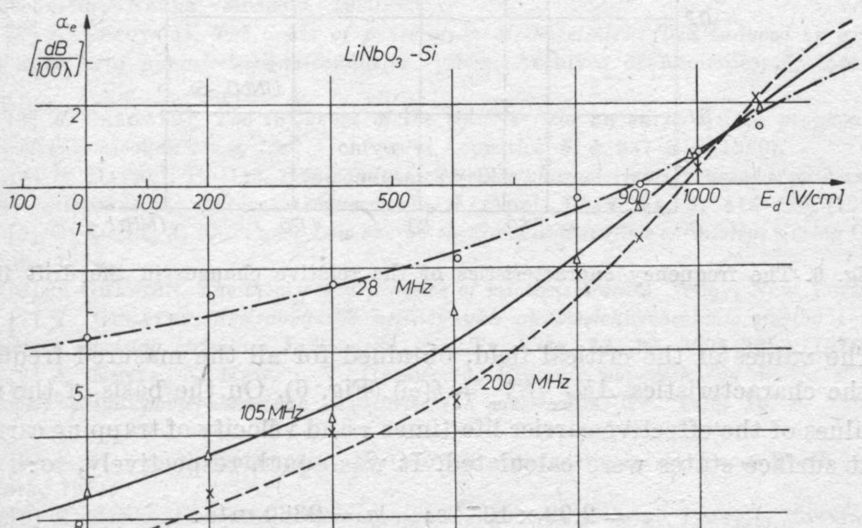

Fig. 5. The characteristics of the electronic attenuation coefficient $\alpha_e = f(E_d)$ for the LiNbO$_3$ – Si system

These waveguide systems enabled the investigations at the following frequencies (having applied the generation of higher harmonics):

for the $LiNbO_3$ waveguide: 12, 28, 36, 60, 85, 105, 130, 140, 160, 200 MHz

for the $Bi_{12}GeO_{20}$ waveguide: 2, 6, 10, 15, 20, 32, 45, 60, 75, 100, 110, 140 MHz.

In order to test the acoustic investigation method on the fast surface states in a semiconductor single, a crystal wafer of the *n*-type (111) Si with the electric conductivity $\sigma = 3\ [\Omega m]^{-1}$, the carrier mobility $\mu_0 = 0.047\ m^2/Vs$, and the dimensions $12 \times 7 \times 0.05\ mm^3$ was used.

Fig. 3 shows a diagram of the experimental set-up for measuring the coefficient of surface wave attenuation. Figs 4 and 5 present the typical characteristics of electronic surface wave attenuation as the drift field function in a semiconductor. The measurements were performed for the (111) Si surface, with the following photoconductivities:

$$\sigma_1 = 3\ \Omega m^{-1}; \quad \sigma_2 = 5\ \Omega m^{-1}; \quad \sigma_3 = 10 \Omega m^{-1}.$$

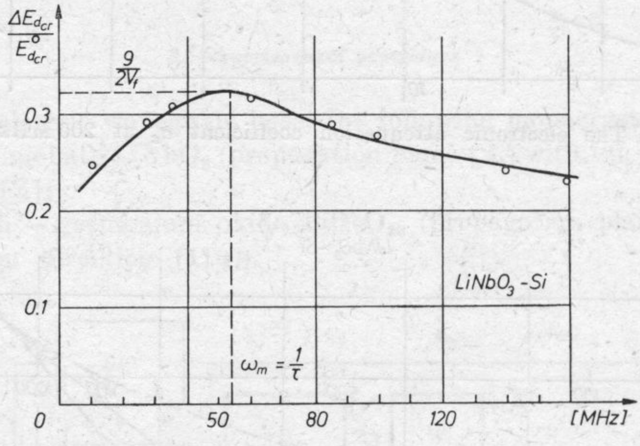

Fig. 6. The frequency characteristics of the relative changes in the drift field

The values of the critical field, obtained for all the masured frequencies, give the characteristics $\Delta E_{d_{cr}}/E^0_{d_{cr}} = f(\omega)$ (Fig. 6). On the basis of the results, the values of the effective carrier life-timee τ and velocity of trapping carriers, g, in fast surface states were calculated. It was equal, respectively, to:

$$\tau = 2.92 \times 10^{-9}\ s; \quad g = 2360\ m/s.$$

The accuracy of determining τ and g was:

$$\frac{\delta\tau}{\tau} = 9.3\,\% \quad \text{and} \quad \frac{\delta g}{g} = 9.1\,\%.$$

Similar values of τ and g for the n-type (111) Si surface, prepared by mechanical treatment, was obtained by RZHANOV [14] as less than 10^{-8} s, but the trapping velocity of those states was of the order of 10^3 m/s.

4. Conclusions

The results obtained show that the new acoustic method presented can be applied to determine the parameters τ and g in investigations of fast surface states in semiconductors. It seems to give better accuracy than the other experimental methods (the values of τ and g can be determined with an accuracy better than 10%). It can be pointed out that this method makes possible dynamic measurements of surface state parameters over the frequency range up to several hundred MHz (or more).

More extensive investigations of the influence of the temperature and pressure of various gases on the parameters of fast surface states in the n-type (111) Si will be published in the future papers.

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