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INVESTIGATIONS CONCERNING FAST SURFACE STATES OF SEMICONDUCTORS BY MEANS OF ACOUSTIC METHODS

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The paper deals with the results of investigations an n-Si surfaces, obtained by determining acoustically the parameters of fast surface states in semiconductors. This new method is theoretically based on the analyses of the influence of surface states in a semiconductor on the propagation of a Rayleigh surface wave in a layer system of piezoelectric and semiconducting layers. It is possible to determine the effective life time τ of the charge carrier of fast surface states, as well as the velocity of recombination, g, of the carriers in these states.

Praca przedstawia doświadczalną weryfikację metody (zaproponowanej wcześniej przez autorów) pomiaru czasu życia oraz prędkości rekombinacji nośników. Pomiary przeprowadzono wykorzystując różne podłoża piezoelektryczne i różne warunki pomiaru próżnia, gaz obojętny. Otrzymane wyniki potwierdzają przydatność zaproponowanej przez autorów metody.

1. Introduction

The papers deals with the results of investigations on n-Si surfaces, obtained by determining acoustically the parameters of fast surface states in semiconductors. This new method is theoretically based on the results presented in [3], where the author analyses the influence of surface states in a semiconductor on the acoustic propagation of the Rayleigh's surface wave in a layer system of piezoelectric and semiconducting layers. Making use of the effect on the interaction of a surface wave and the charge carrier in the semiconductor, to which a longitudinal electric drift field is applied, it is possible to determine the effective life time τ of the charge carrier at fast surface states, as well as the velocity of recombination g of the carriers by these states.

The idea of determining the parameters τ and g consists in the determination of the frequency characteristics of relative changes of the critical drift field [3]:

$$\frac{E_{dcr}-E^0_{dcr}}{E^0_{dcr}} = \frac{\Delta E_{dcr}}{E^0_{dcr}} = \frac{g}{V_f}\cdot\frac{\omega\tau}{1+\omega^2\tau^2}, \tag{1}$$

where E_{dcr} is so-called critical field (the value of the electric field applied to the semiconductor in the direction of propagation of the surface wave, at which the electronic attenuation coefficient of the surface wave is equal to zero), $E^0_{dcr} = V_f/\mu_0$; μ_0 – volumetric mobility of the carriers in the semiconductor, V_f, ω – velocity and frequency of the acoustic surface wave; g – velocity of recombination of the charge carriers at the surface states in the semiconductor; τ – life time of the carriers in surface states.

Basing on the position of the maximum $(E_{dcr}/E^0_{dcr})_{\max}$, on the frequency axis in the characteristics $(E_{dcr}/E^0_{dcr}) = f(\omega)$ we determine the value of τ:

$$\tau = \frac{1}{\omega_m} \tag{2}$$

where ω_m corresponds to $(E_{dcr}/E^0_{dcr})_{\max}$.
The velocity of recombination g is determined by means of the relation

$$g = 2V_f\left(\frac{\Delta E_{dcr}}{E^0_{dcr}}\right)_{\max}. \tag{3}$$

Paper [4] discusses in more detail the theoretical principles of this method the measuring position, as well as the measurement results of the parameters τ and g of surface states in n-Si obtained in atmospheric air.

The present paper deals with the results of investigations on n-Si, previously subjected to a change of the energetic structure of the surface. As the investigated parameters τ and g are affected by external conditions [1, 6], measurements were made taken in vacuum, in various atmospheres surrounding the semiconductor, at various pressures and various temperatures. For this purpose a special vacuum system was constructed, from which it was possible to remove various gases, and in which the silicòn sample could be heated up to a temperature of about 1000 K [5].

The procedure of measurements was the same as that described in [4]. The measurements were carried out on the same measuring stand, supplemented by a vacuum system.

For the sake of comparison, the results of the present paper and those presented in [4] concern the same silicon sample, wave-guide substrates BGO, $LiNbO_3$, frequencies of the surface wave (within the range of 2+200 MHz) and values of electric conductivity ($\sigma_1 = 3[\Omega m]^{-1}$, $\sigma_2 = 5[\Omega m]^{-1}$, $\sigma_3 = 10[\Omega m]^{-1}$ of the n-Si sample.

Changes of the electric conductivity of the n-Si sample were achieved by illuminating it with a halogen lamp.

2. Measurements of the parameters of surface staten in silicon in vacuum

Both, the electronic attenuation coefficient α_e of a surface wave and the critical drift field E_{dcr} have been measured in the piezoelectric silicon system situated in vacuum the pressure in the measuring chamber amounting to $5 \cdot 10^{-4}$ hPa.

Figure 1 provides exemplary characteristics of the electron attenuation coefficient α_e as a function of the electric drift field E_d in a semiconductor.

Figure 2 demonstrates the frequency characteristics of relative changes of the critical drift field (characteristics No. 1). The numerically determined parameters τ and g are equal

$$\tau = (7.70 \pm 0.6) \cdot 10^{-8}\ \text{s},$$
$$g = 900 \pm 70\ \text{m/s}.$$

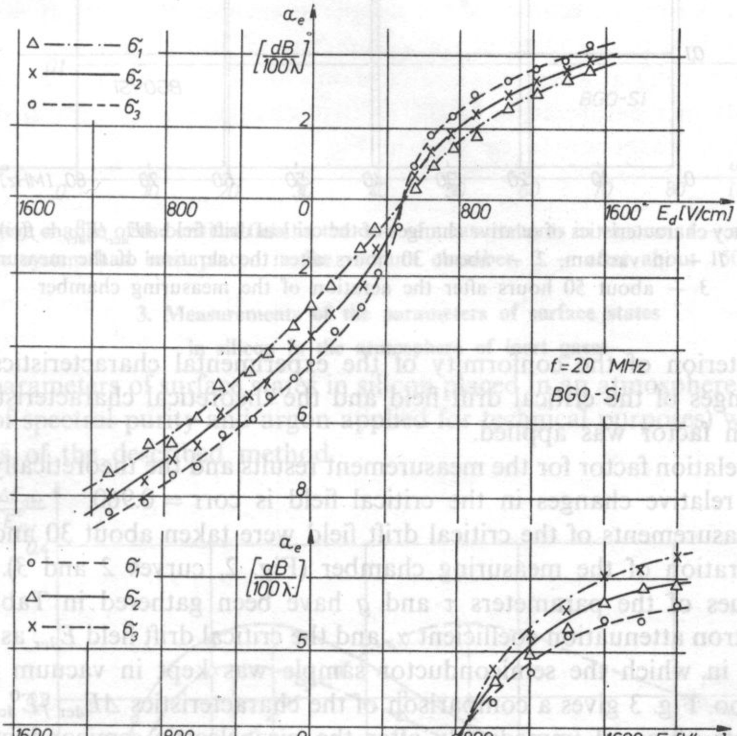

Fig. 1. Exemplary characteristics of the electron attenuation coefficient α_e for various photoconductivities of Si these measurements were made in vacuum

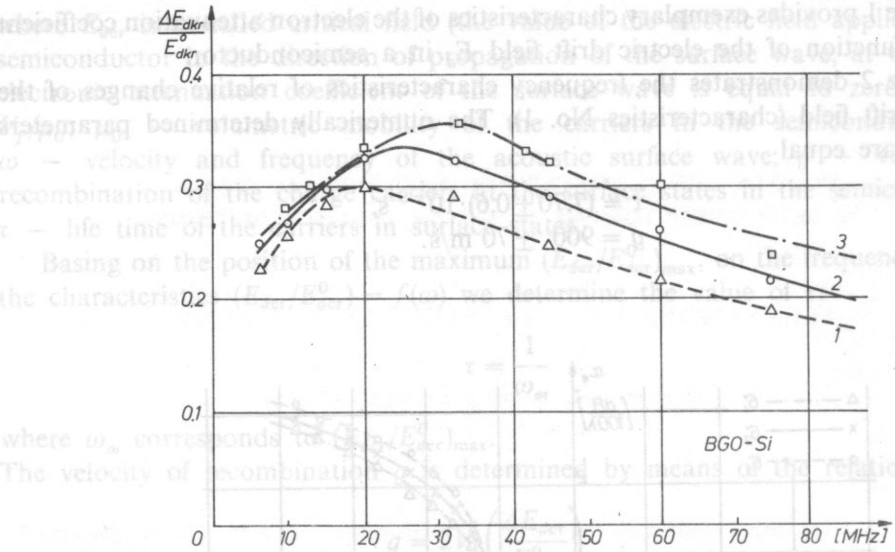

Fig. 2. Frequency characteristics of relative changes of the critical drift field $\Delta E_{dcr}/E^0_{dcr} = f(\omega)$ in the case of measurements: *1* — in vacuum, *2* — about 30 hours after the aeration of the measuring chamber, *3* — about 50 hours after the aeration of the measuring chamber

As a criterion of the conformity of the experimental characteristics with the relative changes of the critical drift field and the theoretical characteristics (Eq. 1) a correlation factor was applied.

The correlation factor for the measurement results and the theoretically predicted function of relative changes in the critical field is corr = 0.960.

Such measurements of the critical drift field were taken about 30 and 50 hours after the aeration of the measuring chamber (Fig. 2, curves *2* and *3*).

The values of the parameters τ and g have been gathered in Table 1.

The electron attenuation coefficient α_e and the critical drift field E_{dcr} as a function of the time in which the semiconductor sample was kept in vacuum have been measured, too. Fig. 3 gives a comparison of the characteristics $\Delta E_{dcr}/E^0_{dcr} = f(\omega)$ of measurements obtained immediately after the piezoelectric semiconductor system had been placed in the vacuum chamber and after about 50 hours. The apparent differences are due to the fact that the vacuum used in these measurements ($5\cdot10^{-4}$ hPa) could not secure and immutability of the silicon surface.

Table 1

		In vacuum	About 30 hours after aeration	About 50 hours after aeration
τ	[s]	$7.7\cdot10^{-9}$	$6.3\cdot10^{-9}$	$5.0\cdot10^{-9}$
g	$\left[\frac{\text{m}}{\text{s}}\right]$	900	1100	1200

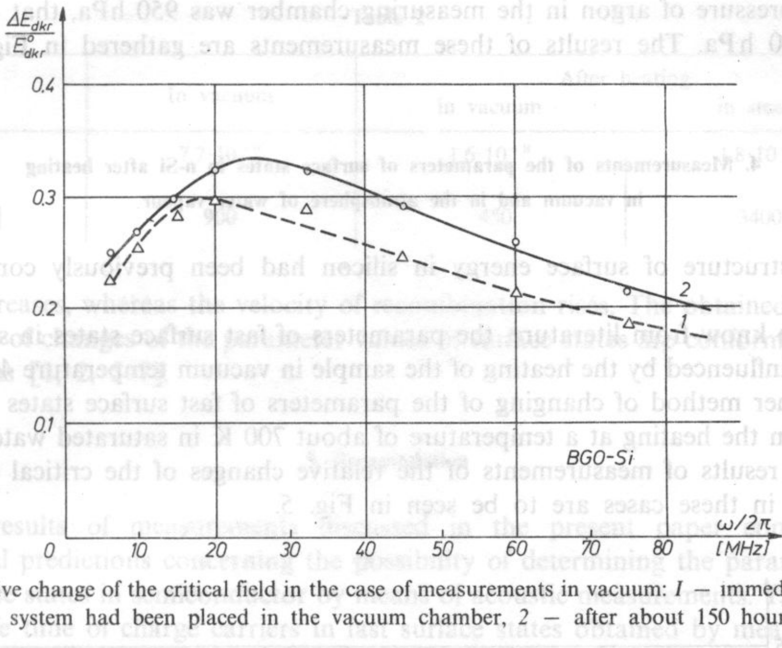

Fig. 3. Relative change of the critical field in the case of measurements in vacuum: *1* — immediately after the system had been placed in the vacuum chamber, *2* — after about 150 hours

3. Measurements of the parameters of surface states in silicon in the atmosphere of inert gases

The parameters of surface states in silicon placed in an atmosphere of inert gases (helium of spectral purity and argon applied for technical purposes) were measured by means of the described method.

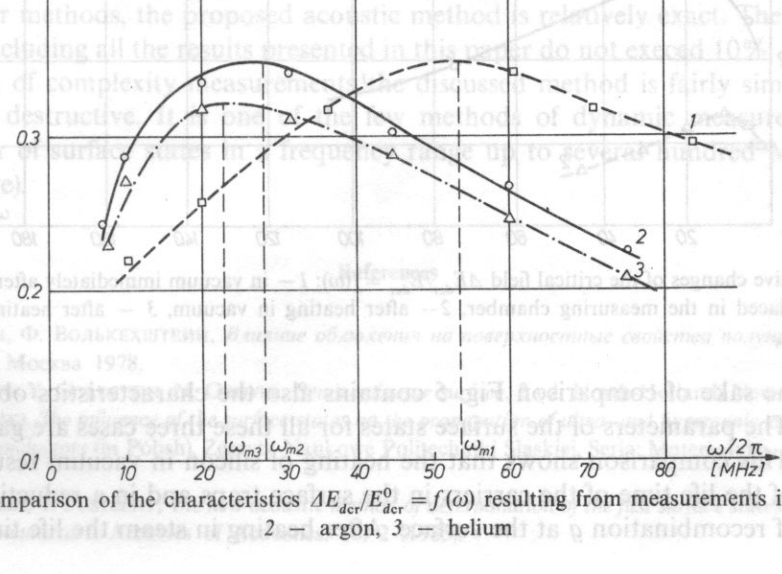

Fig. 4. A comparison of the characteristics $\Delta E_{dcr}/E^0_{dcr} = f(\omega)$ resulting from measurements in: *1* — air, *2* — argon, *3* — helium

The pressure of argon in the measuring chamber was 950 hPa, that of helium about 200 hPa. The results of these measurements are gathered in Fig. 4.

4. Measurements of the parameters of surface states in n-Si after heating in vacuum and in the atmosphere of water vapour

The structure of surface energy in silicon had been previously considecably changed.

As we know from literature, the parameters of fast surface states in silicon are strongly influenced by the heating of the sample in vacuum temperature 400 K [7].

Another method of changing of the parameters of fast surface states in silicon consists in the heating at a temperature of about 700 K in saturated water vapour [2]. The results of measurements of the relative changes of the critical drift field obtained in these cases are to be seen in Fig. 5.

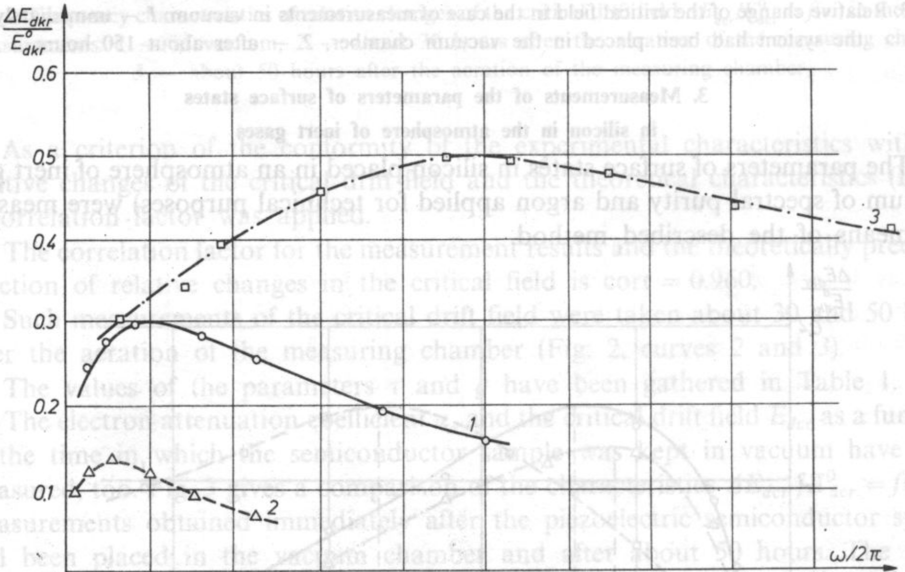

Fig. 5. Relative changes of the critical field $\Delta E_{dcr}/E^0_{dcr} = f(\omega)$: *1* — in vacuum immediately after the system had been placed in the measuring chamber, *2* — after heating in vacuum, *3* — after heating in steam

For the sake of comparison Fig. 5 contains also the characteristics obtained in vacuum. The parameters of the surface states for all these three cases are gathered in Table 2. This comparison shows that the heating of silicon in vacuum results in an increase of the life time of the carriers in the surface traps and in a reduction of the velocity of recombination g at the surface. After heating in steam the life time in the

Table 2

		In vacuum	After heating in vacuum	 in steam
τ	[s]	$7.7\cdot10^{-9}$	$1.6\cdot10^{-8}$	$1.8\cdot10^{-9}$
g	$\left[\frac{m}{s}\right]$	900	450	3400

trape decreases, whereas the velocity of recombination rises. The obtained changes directions of changes of the parameter values of surface states are conform with the predictions [1, 2, 5–7].

5. Recapitulation

The results of measurements discussed in the present paper confirm the theoretical predictions concerning the possibility of determining the parameters of fast surface states in semiconductor by means of acoustic measurements. The values for the life time of charge carriers in fast surface states obtained by means of the acoustic method as well as the velocities of recombination g of the carriers by these states agree with the predictions.

The acoustic method has made it possible – and this is of great significance – to measure simultaneously two important parameters of fast surface states in a wide range:

– the effective life time τ in the traps within the range $10^{-10} \div 10^{-6}$ s,

– the velocity of recombination g up to 10^4 m/s.

In this range of measurements the method in question is one of few. Compared with other methods, the proposed acoustic method is relatively exact. The errors of τ and g including all the results presented in this paper do not execed 10%. From the viewpoint of complexity measurements the discussed method is fairly simple being also non destructive. It is one of the few methods of dynamic measurements of parameter of surface states in a frequency range up to several hundred MHz (and even more).

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