ARCHIVES OF ACOUSTIC
1, 1, 29-32 (1976)

ON THE POSSIBILITY OF AN INVESTIGATION OF SEMI-CONDUCTOR SURFACE PROPERTIES USING ULTRASONIC SURFACE WAVES

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The investigations concerning the propagation of surface waves have so far neglected semiconductors. The present paper points out the necessity of taking into account the effect of surface properties on the propagation of surface waves, even for long ultrasonic waves such that $\lambda \gg r_D$ (λ – wavelength and r_D – Debye radius). Having this in mind some possibilities of determining the electrostatic potential on the basis of acoustical data obtained for the solid material and thin semiconductor layers have been described.

It is possible to calculate the electrostatic potential developed at a thin surface layer which is perturbed by the surface wave, in terms of acoustical data obtained for the bulk material. It is well known that the energy levels of the surface potential are curved and this fact influences the other surface properties of the semiconductors. This curvature is determined from the field effect i.e. when the curve representing the dependence of surface conductivity on applied voltage reaches a minimum.

If the external applied field is shielded by the field associated with the surface states, then the minimum of surface conductivity may not be obtainable and the application of the field effect method is restricted. Other methods require certain models to be assumed for the surface states and they thus provide only indirect information.

Surface wave research suggests new possibilities for the determination of surface potential and surface states. In a piezoelectric medium the surface wave will give rise to a travelling electric field and this in turn is capable of interacting with electrons in the medium of a piezosemiconductor or of medium in contact with a pure piezoelectric.

The following special cases will be considered:

1. The wave is excited in a piezoelectric medium which also exhibits semiconductor properties. The surface wave in this case penetrates into the medium to a depth of the order of a wavelength. Since the thickness of the

layer close to the surface is of the order of the Debye's radius r_D, the surface layer is capable of effecting the surface wave only if $\lambda \leqslant r_D$ (discussed in [2]).

2. The wave propagates in a piezoelectric medium and its accompanying electric field penetrates into the semiconductor which has no acoustical contact with the piezoelectric. The field penetrates into the semiconductor to a depth equal to r_D from the surface. Then the wave propagation parameters depend only on the properties of this layer.

3. The surface wave propagates in the piezoelectric onto which a semiconductor layer of thickness $d \approx r_D$ is deposited, where $r_D \ll \lambda$. If the semiconductor shows no piezoelectric effect, the wave interacts with the carriers through the field generated in the piezoelectric substrate. We do not consider here the interaction through the deformation potential since at low frequencies it is extremely small. In the case of a piezosemiconductor layer, the layer surface is capable of affecting propagation only if the layer thickness $d \approx r_D$, where $\lambda \gg r_D$.

We can use cases 2 and 3 to investigate the properties of the layer close to the surface of solid semiconductors or thin semiconductor layers.

Let us consider a potential barrier corresponding to small absolute values of the electrostatic surface potential $Y_s \ll 1$. In this case, the change in the space charge in the interface layer is also small. The changes in potential are small compared to kT/e, while the properties of the region of the space charge differ only a little from those of the unperturbed portion of the semiconductor. Our discussion was intended to demonstrate the possibility of employing the surface wave for investigating the interface layer. The problem was restricted to considering the effect of the space charge distribution in the interface layer, i.e. the layer close to surface, on the attenuation coefficient α of the surface wave.

The attenuation coefficient for case 2 can be described by the expression

$$\alpha = \eta k F \frac{\varepsilon_1}{\varepsilon_2} \frac{\omega' \tau_M \gamma}{1 + \omega'^2 \tau_M^2 \left(1 + \dfrac{\varepsilon_1}{\varepsilon_2}\right)^2 \gamma^2}, \tag{1}$$

where η – electromechanical coupling constant, $k = 2\pi/\lambda$ – wave number, F – positive number which depends slightly on piezoelectric modulus, ε_1, ε_2, ε_0 – permittivities of the substrate, the semiconductor and the vacuum respectively, $\tau = \varepsilon_2 \varepsilon_0 / \sigma = \tau_M$ – Maxwell relaxation time for a semiconductor, $\omega = 2\pi\nu - \nu$ denotes frequency, σ – specific conductivity, $\gamma = 1 - f\mu E_0 / v_s$, $\omega' = \omega - k v_d$, where v_d – drift velocity and v_s – propagation velocity, μ – mobility and E_0 – the drift field.

It should be taken into account that, in the case under consideration, the carrier concentration is a function of the penetration depth n_0 in the semiconductor without the electrical field which accompanies the acoustic wave. For this reason, we should determine the average value of the electric conductivity $\langle\sigma\rangle$, which determines the absorption of acoustical energy.

In the layer close to the surface for $Y_s \ll 1$, the electrostatic potential is given by the following function of the depth

$$Y = Y_s \exp(-z/r_D), \tag{2}$$

where

$$r_D = \left[\frac{\varepsilon\varepsilon_0 k\sigma}{2\pi e^2(n_0+p_0)}\right]^{1/2}.$$

The carrier concentration is expressed as follows:

$$n_0(z) = n_\infty(1 - Y_s e^{-z/r_D}). \tag{3}$$

Then

$$\langle\sigma\rangle = \left[\frac{1}{r_D}\int_0^{r_D} n_{00}(1 - Y_s e^{-z/r_D})\,dz\right] e\mu. \tag{4}$$

The corresponding calculated field

$$\langle\vec{\sigma}\rangle = \sigma(1 - 0.6\,Y_s). \tag{5}$$

Insertion of (5) into (1) provides

$$a = \eta kF \frac{\varepsilon_1}{\varepsilon_2} \frac{\omega' \tau_M (1 - 0.6\,Y_s)\gamma}{1 + \omega^2\tau_M^2(1 + 1.2\,Y_s)\left(1 + \frac{\varepsilon_1}{\varepsilon_2}\right)^2 \gamma^2}. \tag{6}$$

It follows from (6) that the attenuation coefficient a is related to the electrostatic surface potential. Hence, from measurements of the attenuation coefficient resulting from the interaction between the surface wave and electrons it is possible to determine how the energy bands are curved on the semiconductor surface.

We can suggest here the following procedures:

1. The surface potential is determined directly from measurements of the attenuation coefficient. To do this, we have to know the remaining quantities involved in (6) which describe the semiconductor properties.

2. In order to determine the surface potential, we change the frequency or the conductivity in the bulk of the semiconductor and make use of the relation between these quantities and the attenuation coefficient.

The curves $a = a(\omega)$ and $a = a(\sigma)$ have maximum values at positions depending on the magnitude of the curvature of the energy bands.

Thus the curve $a = a(\omega)$ has its maximum at

$$\omega = \frac{1 - 0.6\,Y_s}{\tau_M\left(1 + \frac{\varepsilon_1}{\varepsilon_2}\right)}, \tag{7}$$

while for the curve $\alpha = \alpha(\sigma)$ it is at

$$\sigma = \omega(\varepsilon_1 + \varepsilon_2)(1 + 0.6\,Y_s). \tag{8}$$

3. The maximum of the curve $\alpha = \alpha(\gamma)$ (8) occurs when

$$\gamma = (1 + 0.6\,Y_s)/\omega\tau_M.$$

Conclusions

It follows from the above discussion that the method of ultrasonic surface waves (including also the case $\lambda \gg r_D$) can be employed for determining the electrostatic surface potential in solid semiconductors and thin semiconductor layers. Various measuring methods are used. Their choice depends on what quantities are known characterizing the bulk properties of the semiconductor.

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Received 6th January 1975