ABSTRACT

In this work, we investigated the interaction of surface acoustic waves (SAW), propagating on the surface of a piezoelectric substrate of Lithium Niobate ($LiNbO_3$), with charge carriers in ultra-thin metallic films, deposited along the path of propagation.

The piezoelectric field accompanied by the SAW bunches the charge carriers in the film in the direction of propagation. This drag of the space charge includes an electric field which, by piezoelectricity, excites another SAW, which is not in phase with the original one. The two SAWs interfere with each other causing an attenuation and dispersion of the SAW. The phase difference between the two waves is dependent mostly upon the conductivity "thickness" of the film. The theory of this interaction is based upon a theory formulated by Hutson and White, with certain extensions to our case.

Three frequencies are involved in the interaction as derived by Hutson and White:

(1) SAW frequency ω

(2) Dielectric relaxation frequency ω_C

(3) Diffusion frequency ω_D

The first one is determined by the geometry of the substrate and of the interdigited transducer, used to excite the SAW.

The second one is proportional to the sheet conductivity of the film prepared by vacuum evaporation at about 10^{-6} torr.

The third depends on the mobility of the charge carriers in the film and the Einstein relation concerned.

An experimental verification, of the interaction, was done by Bierbaum.[10] He measured the attenuation of the SAW as a function of sheet resistivity. From the maximum attenuation measured, and the following assumptions:

(1) The mobility of the charge carriers in the film is constant

(2) The Einstein relation is satisfied with Fermi energy

(3) The Fermi energy of the system of charge carriers in the film is constant, and is equal to that of the bulk

he obtained the parameter ω_D from which the product of mobility and Fermi energy μE_F of the charge carriers, could be determined. Using assumption (3) Bierbaum had estimated the mobility of charge carriers. The values that were obtained by Bierbaum for mobilities were very close to those in the bulk.

In this work, we measured, by means of a SAW oscillator, the change in phase velocity of the SAW, which had not be measured before. In the experimental system used, we were able to measure simultaneously the attenuation and the change in phase velocity of the SAW.

Theoretically, the maximum fractional change in phase velocity is equal to what is called the electromechanical coupling constant of the substrate. In our case for $LiNbO_3$ this constant is relatively high (0.024). Hence very small changes in phase velocity could be measured.

This facility of simultaneous measurement of attenuation and change in velocity of SAW offers a number of advantages.

I. Subtantional tool is provided to investigate and justify the theory.

II. The product μE_p could be measured by:

(a) The maximum attenuation α_{max} of the SAW

(b) The slope and intercept of the line describing the quotient of the fractional change in velocity/attenuation as a function of the resistivity per square of the film R

Bierbaum could find this product from (a) only. The correspondence between the three values of the product μE_p obtained from (a) and (b) was very rare. Usually, a good correspondence exists between the values of μE_p obtained from α_{max} and the intercept $\frac{\Delta v}{v\alpha}$ (R).

The conclusion is that the resistivity of the film was found to be an unreliable, parameter. Shifts of the curves α and $\frac{\Delta v}{v}$ as functions of this parameter were found to vary from one experiment to the other. Hence it was of great importance to eliminate this parameter and to obtain α as a function of $\frac{\Delta v}{v}$. The correspondence between theoretically predicted curves and experimental curves was quite good.

We found it valuable to get experimentally, and in a continuous run the curve of α $(\frac{\Delta v}{v})$ for the following reasons:

(a) It reduces contamination, gas adsorption and temperature gradients.

(b) It makes calculations simple.

(c) It could give a direct insight on the extent of homogenity of the film.

For these reasons, a new electronic system with SAW oscillator, mixer, filter and frequency to voltage converter, was constructed and developed to display α as a function of $\frac{\Delta v}{v}$.

Usually the experimental curves obtained were not quite symmetric as predicted by theory if ω_D is assumed to be a constant parameter. The conclusion was that we must treat ω_D as a varying parameter in the course of interaction.

In order to find this variation, we rewrote the two expressions of α and $\frac{\Delta v}{v}$ as function of two new parameters n and m where $n = \frac{\omega_C}{\omega} = \frac{\sigma}{\varepsilon\omega}$, and $m = \omega/\omega_D$, σ being the conductivity of the film ε the permitivity constant, and ω the SAW frequency. Letting n to run from zero (at the beginning of evaporation) to great values (thick film) we could find the values of m which must be taken for each n in order to fit to the experimental curve $\alpha\ (\frac{\Delta v}{v})$. Tracing the whole curve, we could obtain by this method the parameter m as a function of n. This parameter, following Bierbaum, includes directly the product μE_p. Since ω_D changes, the product changes in the same way. In order to eliminate each variable in the product, we have to try to measure, at least, one of them separately as a function of n.

We found it easier to measure μ as a function of n utilizing the acoustoelectric effect in the same interaction. It is possible to measure the mobility if the acoustoelectric current I_{ae}. Through the film could be measured simultaneously, as a function of α, together with $\alpha = \alpha\ (\frac{\Delta v}{v})$.

An additional system was used to make it possible to record $\alpha = \alpha\ (\frac{\Delta v}{v})$ and $I_{ae} = I_{ae}\ (\alpha)$ simultaneously on two separate X - Y recorders. Using the theoretical expression for $I_{ae}\ (\alpha)$, μ could be determined for each value of α.

From $\alpha = \alpha\left(\frac{\Delta V}{V}\right)$ each α corresponds to a certain n, so μ as a function of n could be determined.

We can thus determine:

(1) μE_F as a function of n from analysis of the curve $\alpha = \alpha\left(\frac{\Delta V}{V}\right)$, and

(2) μ as a function of n from the curve $I_{ae}(\alpha)$.

By these results, E_F as a function of n could be eliminated.

The main conclusions concerning this part were:

I. μ is not a constant. It increases while n is increasing.

II. The maximum value of μ obtained is at most less by two orders of magnitudes than its value in the bulk.

III. Values for E_F were two orders of magnitude greater than in the bulk.

IV. E_F as a function of n changes in an arbitrary manner.

These conclusions were verified by many experiments performed with various ultra-thin metal films.

Conclusions I - IV make Bierbaum's model and assumptions implausible and doubtful.

From what was mentioned above, stems the necessity of developing a new model which could describe and account for:

(a) Diffusion effects on the interaction in ultra-thin metal films.

(b) The form that the Einstein relation takes for granular island thin film.

We tried a model which is based on a model proposed by Neugebauer and Webb (28). It assumes the film to consist of a planar array of many very small islands of size r and separation R between them.

According to this model, the conduction process consists of, first, charge carrier creation which is thermally activated and involves charge transfer between initially neutral particles. Charge transfer between Islands particles occurs by tunneling.

Using this model we found that:

(1) The Einstein relation is satisfied, but with energy kT.

(2) $\omega_D >> \omega$, such that ω/ω_D can be neglected and no more diffusion terms appear in the interaction.

(3) The electron resides on a charged island for an average finite time τ, which is inversely proportional to r^2.

(4) Due to (3), the interaction has a relaxation process and hence the mobility is complex which also leads to complex conductivity.

(5) Considering (4), and following the theory of Hutson and White, we got new expressions for α and $\frac{\Delta V}{V}$ with $\omega\tau$ as a parameter instead of ω_D.

(6) This model can explain qualitatively the experimental variations of the new parameter $\omega\tau$ as a function of n and it corelates this variation to the different stages of growth of the film.

Still, this model has certain deficiencies:

(1) It does not consider the geometry of the islands and their distribution on the substrate.

(2) It cannot explain the decrease in the mobility at the early stages of growth, especially observed in films with high degree of inhomogenity.