JOURNAL OF SOLID STATE CHEMISTRY 12, 225–231 (1975)

The Acoustic Properties of Oxide Films and Their Application to Acoustic Surface Wave Devices*

FRED S. HICKERNELL

Motorola Government Electronics Division, Scottsdale, Arizona 85252

Received July 3, 1974

Surface acoustic wave techniques represent a powerful tool for the study of the elastic properties of thin film layers. Simple arrays of interdigital transducers can be used to measure the velocity, attenuation, and piezoelectric properties of oxide films. Results of such measurements on zinc oxide and silicon dioxide films are given and the values compared to their bulk counterparts. High acoustic quality oxide films can be used effectively to enhance the performance of surface acoustic wave devices. Potential application areas are briefly summarized.

Introduction

Crystalline oxides have played a prominent role in the study of the elastic properties of matter and in the development of acoustic devices at ultrasonic frequencies. Quartz has long been the standard piezoelectric material used for temperature stable, high Q resonator applications and as a transducer plate for exciting bulk waves in solids. The advent of the microwave acoustic era in the 1960's led to the development of zinc oxide (ZnO) films for the excitation of bulk waves in such low propagation loss crystalline solids as sapphire (Al_2O_3) and spinel ($MgAl_2O_4$) to form microwave delay lines. In the mid 1960's a simple technique for generating and detecting acoustic surface waves on piezoelectric solids was identified (*1*). This has led to a variety of device applications in electronic systems. Two oxide materials, lithium niobate ($LiNbO_3$) and quartz (SiO_2) have dominated these developments.

The serious examination of the theoretical and experimental surface acoustic properties of film layers began around 1969. Considerable theoretical information on the anticipated behavior of oxide films has been developed (*2*, *3*) but only a small amount of experimental data has been reported. The experimental tools are readily available, the techniques are simple and a number of oxide film materials are yet to be investigated. It is the purpose of this paper to describe a simple technique for studying the acoustic properties of oxide films, to present the results of some measurements on SiO_2 and ZnO films and to give examples of how these films are being applied to enhance the performance and broaden the applicability of acoustic surface wave devices.

The basic approach to measurement described in this paper is the use of channelized arrays of interdigital transducers in conjunction with film layers on a piezoelectric (or nonpiezoelectric) substrate. Simple pulse amplitude measurements between various combinations of channelized transducers as a function of frequency, give sufficient information to determine the velocity, attenuation, and coupling factor of film layers. SiO_2 and ZnO films have been measured using these techniques to determine their acoustic properties and compare them to their bulk counterparts. The SiO_2 films described have been chemically deposited or oxidized on silicon substrates. The ZnO is dc triode sputtered and forms as a fine-grain structure of oriented crystallites which is piezoelectrically active (*4*).

* Invited paper.

Such films have been used in the basic exploratory development of surface wave devices and have properties which lend themselves to the integration of acoustic and semiconductor devices on silicon.

The Acoustic Surface Wave Concept

The concept of generating and detecting surface waves on a polished piezoelectric substrate using a thin metal interdigital pattern was first experimentally demonstrated by White and Voltmer (*1*). Figure 1 illustrates a simple acoustic surface wave structure on a piezoelectric plate with a generating and receiving transducer pattern and the displacement pattern of the surface wave near the substrate surface. The surface wave, generated bidirectionally at the transducer structure, is commonly called a Rayleigh wave. It has a retrograde elliptical particle motion at the surface made up of compressional and shearing displacements which decrease rapidly in amplitude into the depth of the solid. The periodicity of the interdigital pattern determines the frequency at which a maximum amplitude wave is generated with adjacent finger positions corresponding to one-half an acoustic wavelength. The number of interdigital finger pairs determines the frequency bandwidth (fractional bandwidth is inversely proportional to the number of finger pairs) and the separation of the transducers establishes a characteristic time delay inversely proportional to the surface wave velocity.

The properties of this simple surface wave structure can be comprehensively characterized by knowing the geometrical configuration and separation of the interdigital patterns, the dielectric permittivity and the basic surface wave acoustic constants of velocity, coupling factor, and attenuation. It is these latter three constants which are the key parameters to be measured in assessing the surface acoustic properties of oxide films.

The Measurement of Film Properties with Interdigital Transducer Arrays

The structure of Fig. 1 can be used for the measurement of the acoustic surface wave velocity and attenuation of a film which is deposited in the propagation path between the two interdigital transducers. Such measurements are most commonly made in a vacuum system during the deposition of a metal or oxide film while monitoring phase changes and pulse amplitude level as a function of film thickness. Some very unique and interesting acoustic properties are displayed particularly with regards to the initial nucleation and growth phases of the films. Such measurements can be correlated with electrical and microscopic data to give a more compre-

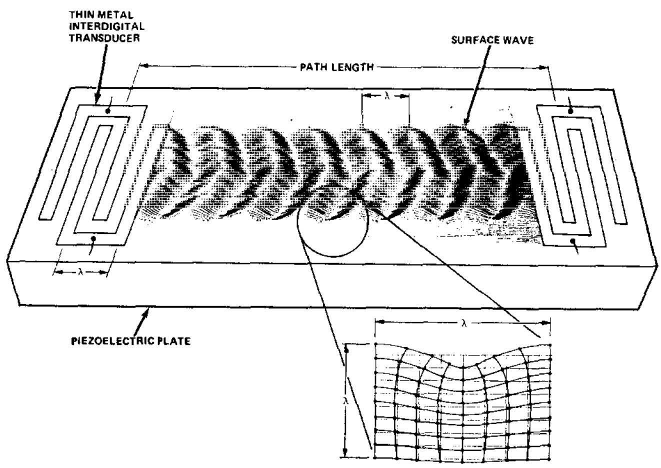

FIG. 1. A basic acoustic surface wave structure with two interdigital thin metal transducer patterns on a piezoelectric plate.

hensive picture of the structural development of films during growth. Such acoustic measurements can be used to optimize the growth conditions of films.

A most versatile structure for the study of the surface acoustic properties of oxide films is an array of interdigital transducers, variations of which are represented diagrammatically in Fig. 2. A polished substrate of a piezoelectric or nonpiezoelectric material forms the base upon which arrays of interdigital transducers and film structures are formed. The most common structure used for measurement of the properties of a nonpiezoelectric oxide film would be a piezoelectric substrate with several linear channels of aluminum interdigital structures upon which the oxide film is deposited. The film is etched to expose transducer bond pads and the film can be removed completely from one or more of the channels to be used as a reference. An alternative structure can be developed by placing the transducers on top of the film. Piezoelectric films can be used with a piezoelectric or nonpiezoelectric substrate.

The basic measurement to be performed is the excitation of one of the transducers with an rf pulse and the subsequent measurement of its time delay and loss as it is detected at successive taps. The decrease in pulse amplitude at each successive tap is a measure of propagation loss and the velocity can be calculated from the time delay and transducer spacing. A more accurate measurement of velocity is obtained by taking the frequency characteristic using two adjacent transducers. The center frequency of the main lobe of the $\sin x/x$ characteristic multiplied by the period of the interdigital transducer gives the velocity. The adjacent sidelobes and nulls can be used to characterize the velocity change as a function of film thickness to acoustic wavelength.

The coupling factor, k^2, for film layers on substrates will vary as a function of film thickness to wavelength ratio (*2*). The value of k^2 can be calculated from a simple theoretical equivalent circuit model involving the values of transducer conversion loss, capacitance, velocity, and the geometry of the interdigital transducer (*5*). With a series of linear transducers it is possible to assign a unique value of conversion loss to a transducer by measuring the insertion loss between it and its adjacent transducers and directly between the adjacent transducers. These three insertion loss values can be used in three linear algebraic relations where each transducer is assigned a conversion loss and each region between transducers a propagation loss. By carrying the measurements to a larger number of linear transducers

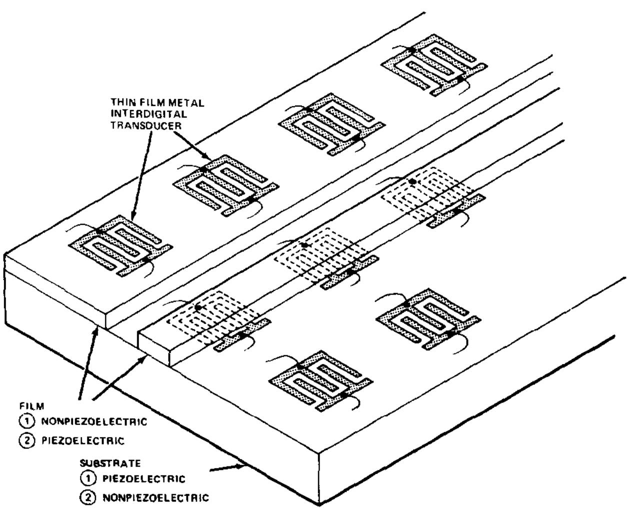

FIG. 2. Interdigital transducer array geometries for the measurement of the acoustic surface wave properties of films.

TABLE I

ACOUSTIC SURFACE WAVE PROPERTIES OF SINGLE CRYSTAL OXIDES

Crystal	Orientation	Velocity (m/s)	Attenuation (dB/μs at 500 MHz)	Coupling factor (k^2)
SiO_2	*ST*	3160	1.0	0.0012
$LiNbO_3$	*YZ*	3480	0.3	0.049
$Bi_{12}GeO_{20}$	(111)(110)	1710	0.4	0.016

and taking loss measurements with various combinations, values of both propagation loss and conversion loss can be determined.

A variety of crystalline piezoelectric substrates may be selected for use. Table 1 gives the three most commonly used piezoelectrics together with values of surface wave velocity, attenuation and coupling factor. Surface wave velocity varies from 1710 m/s for bismuth germanium oxide to 3480 m/s for lithium niobate. Propagation attenuation is comparatively low in these materials. Lithium niobate has a high k^2 coupling factor giving it a capability for the low conversion loss and wide bandwidth excitation of surface waves.

The highest fundamental frequency capability of interdigital transducers is restricted to the UHF region due to the velocity values indicated in Table I and the limits on photolithographic processing. This frequency regime is characterized by micron acoustic wavelengths and is of special interest because most of the surface wave energy can be confined to the film. The interdigital structures have harmonic frequency responses which can be enhanced by the proper selection of the width to space ratio of the fingers. It is therefore possible to generate higher frequency data through harmonic operation.

The area over which the interdigital arrays may be developed is restricted by material and processing constraints. In general, substrate sizes up to 2 in. × 4 in. can be obtained with lithium niobate and quartz which are more than adequate for most evaluations.

In the selection of a piezoelectric substrate it is advantageous to use a fast velocity substrate with a lower velocity film. This minimizes the radiation of surface wave energy from film to solid. Thin aluminum metal films are commonly used as the interdigital electrodes to minimize acoustic loading and scattering of the surface waves.

The Acoustic Surface Wave Properties of SiO_2 and ZnO Films

The acoustics surface wave properties of ZnO and SiO_2 are of interest because of their applicability to improving surface wave device characteristics. The measurements described in this section are used to illustrate the techniques and indicate the surface acoustic quality of the films. A more detailed treatment of the zinc oxide measurements is contained in a recent publication (*6*).

An example of attenuation data taken on a 1.7 μm SiO_2 film chemically deposited on quartz and lithium niobate is shown in Fig. 3.

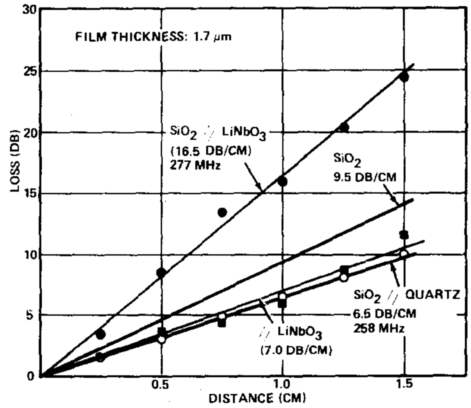

FIG. 3. Acoustic surface wave propagation losses for chemically deposited silicon dioxide films on quartz and lithium niobate.

Seven in-line 20 finger pair aluminum film transducers were used having a periodicity of 12.2 μm. Measurement of the 277 MHz rf pulse amplitude at successive interdigital taps on the $LiNbO_3$ gave a loss of 16.5 dB/cm. Using the reference channel without the film gave 7.0 dB/cm yielding a loss contribution of 9.5 dB/cm for the SiO_2 film. On quartz the loss parameter was 6.5 dB/cm at 258 MHz and the loss in the reference channel was only a few tenths of a dB/cm. The higher loss observed with the $LiNbO_3$ alone comes from the presence of the metal transducers on this high coupling factor material. The quartz provides a better substrate for the growth of a lower acoustic loss SiO_2 film than the $LiNbO_3$. A similar result was obtained by Smith in the measurement of SiO_x films on $LiNbO_3$ and quartz during film growth in a vacuum (7).

Table II summarizes the best results obtained on the measurement of SiO_2 and ZnO films. The ZnO films were sputtered on fused quartz and oxidized silicon. The frequency at which the loss was taken and the film thickness to acoustic wavelength ratio (a measure of how much energy is in the film) is given in the table. The final loss column is what would be the estimated surface wave propagation loss from a polished substrate of fused quartz and crystalline zinc oxide at the frequency indicated. The measurements indicate that oxidized SiO_2 on silicon and sputtered zinc oxide film layers have loss values approaching their bulk counterparts. The quality of the chemically deposited SiO_2 is poorer.

Figure 4 is a velocity characteristic developed as a function of film thickness to wavelength ratio for zinc oxide on SiO_2. Two experimental plots are shown together with the theoretically predicted dependence using bulk material constants. Both of the experimental curves fall below theoretical. The lower curve was developed using the harmonic response of a pair of 200 μm periodicity interdigital structures underlying the ZnO film on fused quartz. Odd harmonics up to the 29th were used and the frequency of maximum pulse amplitude was measured. The frequency range of measurement was 16–250 MHz with film thickness to wavelength ratios up to 0.7.

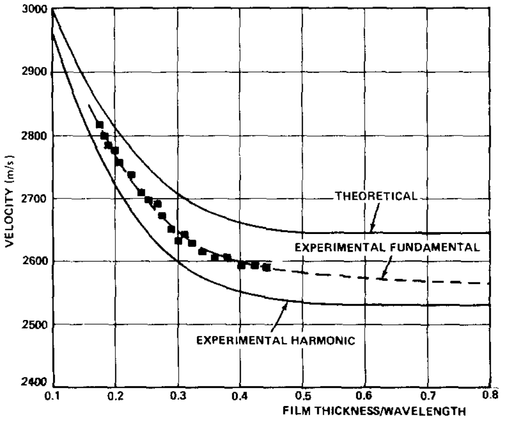

FIG. 4. Phase velocity for ZnO films on fused quartz.

The second experimental curve in Fig. 4 is based on measurements taken using the $\sin x/x$ frequency characteristic of a 12 μm periodic pattern for ZnO on a thick oxidized layer of silicon. The nulls and peaks of the sidelobe pattern in the 180–250 MHz range were used to develop the characteristic. The

TABLE II

ACOUSTIC SURFACE WAVE PROPAGATION LOSS IN SiO_2 AND ZnO FILMS

Film	Frequency (MHz)	Thickness/wavelength	Film loss (dB/μs)	Loss (dB/μs)
Chemical SiO_2	258	0.15	2.0	—
Chemical SiO_2	840	0.45	26.0	7.0
Oxidized SiO_2/Si	346	0.65	2.0	1.5
Sputtered ZnO	220	0.20	1.5	—
Sputtered ZnO	630	1.0	8.0	6.0

two experimental curves differ from theoretical and this difference is most pronounced in the higher thickness to wavelength region where the surface wave energy is almost totally in the ZnO film. The results are very repeatable and due to the structure of the films. The lower curve was developed from film regions having a rough surface texture and crystallites which did not have their *C*-axis highly oriented to the substrate normal. The curve the closest to theoretical was developed in film regions with a clear microscopic appearance, smooth surface and well oriented crystallites.

Figure 5 is a plot of k^2 coupling factor as a function of film thickness to wavelength ratio for ZnO film layers on fused quartz and oxidized silicon. The data points were developed using measured insertion loss data above 200 MHz from a series of in-line transducers (periodicity of 12 μm) to determine conversion loss of individual structures. The coupling factor was calculated using an equivalent circuit model which required measured input data of velocity, dielectric permitivity, and the geometrical parameters of the interdigital structure. The solid line gives the expected theoretical values and the dashed line with plot points are the measured values taken in smooth, clear, well-oriented film areas. The lower experimental dashed line indicates the average value of coupling factor in areas outside the clear region which are characterized by a rougher and less well oriented film. The thickest that high coupling factor films could be grown was just above 4 μm. Beyond this thickness the film quality degraded and the k^2 values were those indicated by the lower curve.

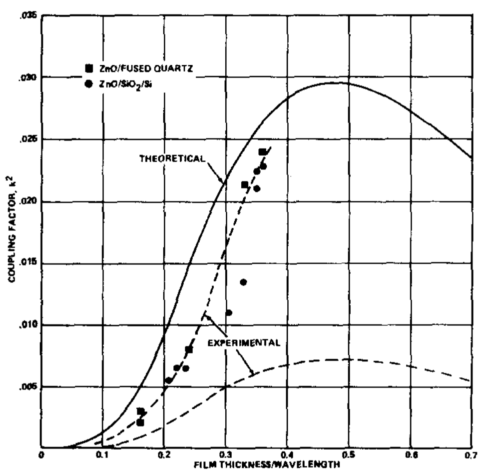

FIG. 5. Calculated and measured k^2 coupling factor values for ZnO film layers on fused quartz and oxidized silicon.

The measurement of attenuation, velocity, and k^2 coupling factor for the ZnO films served to establish the deposition conditions that were essential in obtaining a high quality film. Films possessing acoustic properties which approached that of a single crystal were found to be made up of a fine grain structure (average crystallite size under 200 Å) with strong *C*-axis normal orientation ($\pm 5°$), a smooth surface texture and transparent optical properties.

Applications of Oxide Films to Acoustic Surface Wave Devices

The application of film layers to acoustic surface wave devices has been the subject of a recent paper and will not be discussed in detail here (*8*). Oxide film layers can be used effectively to improve the performance characteristics of piezoelectric based components, enhance interactive processes in active devices, and bring about a melding of acoustic surface wave and semiconductor technologies in monolithic form to produce high density, low cost signal processing circuitry. Zinc oxide and silicon dioxide films have been used to alter the coupling factor on piezoelectrics, as waveguides, to minimize the temperature coefficient of delay, for high frequency wave excitation and to reduce deleterious second order effects. Zinc oxide has been explored as a viable material for the development of acoustic traveling wave amplifiers, convolvers, and integrated acoustooptic circuitry.

The establishment of a silicon based acoustic surface wave technology offers tremendous possibilities for the integration of acoustic and semiconductor circuitry. One of the most direct approaches is the use of zinc oxide as the piezoelectric film for surface wave excitation and arrayed MOSFET detectors to form a tapped delay line. This basic delay line can be used to develop programmable phase coded matched filter circuits with built-in coding, switching and amplification to yield a highly versatile signal processing device.

Conclusions

This paper has presented a simple measurement technique using interdigital transducer arrays for the evaluation of three basic surface acoustic wave parameters, velocity, attenuation and coupling factor. These parameters can characterize the basic acoustic properties of oxide films and be used as effective measures in developing deposition parameters to produce high quality oxide film layers. Measurements made on sputtered ZnO films have indicated that acoustic properties approaching those of bulk materials can be obtained. The quality of oxidized SiO_2 on silicon approaches that of fused quartz regarding attenuation, whereas chemically deposited SiO_2 is of poorer acoustic quality.

A worthy goal in the investigation of the acoustic properties of films is to accurately characterize the elastic constants, piezoelectric coefficients, and physical and structural properties which collectively give rise to the observed surface wave velocity, attenuation, and coupling factor. This undertaking will require good theoretical models, clever test structures, and high quality films for measurement.

Oxide films can play a significant role in extending the capabilities of acoustic surface wave devices. To fulfill their promise a concentrated work effort is required in developing high acoustic quality oxide film layers with reproducible properties over large substrate areas.

Acknowledgments

The author wishes to acknowledge the invaluable technical assistance of John Brewer in the deposition and growth of ZnO and SiO_2, and Al Kapanicas in assisting with film measurements.

References

1. R. M. White and F. W. Voltmer, *Appl. Phys. Letters* **7**, 314 (1965).
2. G. S. Kino and R. S. Wagers, *J. Appl. Phys* **44**, 1480 (1973).
3. L. Solie, *J. Appl. Phys.* **44**, 619 (1973).
4. F. S. Hickernell and J. W. Brewer, *Appl. Phys. Letters* **21**, 389 (1972).
5. W. R. Smith, H. M. Gerard, J. H. Collins, T. M. Reeder, and H. J. Shaw, *IEEE Trans. MTT* **17**, 856 (1969).
6. F. S. Hickernell, *J. Appl. Phys.* **44**, 1061 (1973).
7. W. R. Smith, *Technical Report M.L. 1821, Microwave Laboratory, Stanford University* (1970).
8. F. S. Hickernell, *Proceedings of the Conference on Component Performance and Systems Applications of Surface Acoustic Wave Devices* **11**, (1973).