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**HIGH FREQUENCY LOW LOSS
SURFACE ACOUSTIC WAVE FILTERS**

by

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**A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Electrical and Computer Engineering
in the College of Engineering
at the University of Central Florida
Orlando, Florida**

**Summer Term
1996**

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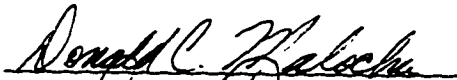
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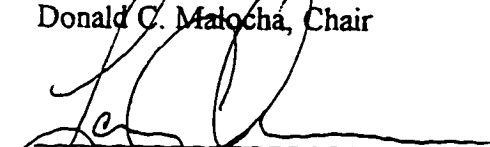
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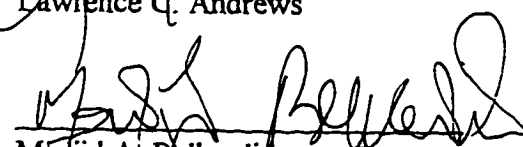
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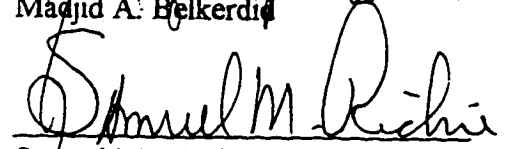
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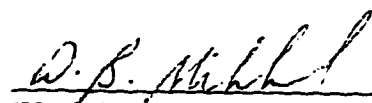

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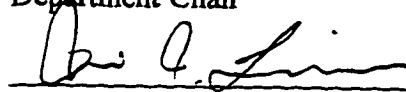

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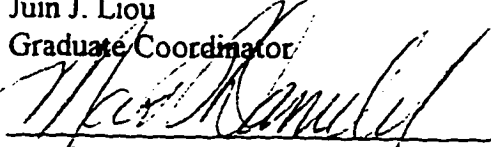

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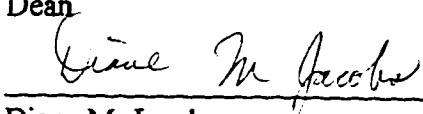

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ABSTRACT

Surface acoustic wave (SAW) devices are currently being utilized in numerous systems with frequencies in the 1.8-1.9 GHz range, and at 2.5 GHz, with developing applications at up to 5.8 GHz. Applications requiring SAW filters at high frequencies not attainable using conventional transducer structures and lithographic techniques have sparked considerable interest in alternative methods for achieving high frequency performance. Low-loss SAW devices are required for certain applications where system noise figure or dynamic range cannot accommodate the higher loss typical of bi-directional SAW filters. This work describes a multilevel, half-wavelength transducer structure for high frequency SAW device fabrication, and demonstrates its usefulness for high frequency operation. Applicability to low-loss devices is discussed, and low-loss performance is demonstrated using a device with group type unidirectional transducers (GUDTs). The multilevel transducer configuration inherently lacks internal reflections, has enhanced harmonic performance, and can be fabricated using only conventional SAW fabrication techniques. One version of the fabrication process requires no critical alignment steps, and is inherently manufacturable. The transducer structure, materials and fabrication techniques are described, and a transmission line equivalent circuit model for the devices is derived. An equivalent circuit parameter extraction technique is used to obtain values for parameters necessary for modeling device performance. Experimental results are shown

for several devices fabricated with multilevel transducers, including simple unapodized bi-directional filters, apodized filters, and low-loss group type unidirectional transducer (GUDT) devices. Comparison is made between experimental results and results of the transmission line model. Device fundamental operating frequencies ranging from 100 MHz to 1.8 GHz are demonstrated, with losses ranging from 8.5 dB to over 30 dB.

This dissertation is dedicated to my husband, Andrew Jerome Hines, and to my son Andrew Thomas and daughter Elizabeth Suzanne, all of whom sacrificed considerably to enable me to pursue this work. Without the continual understanding, support, and loving encouragement of my husband, I would have been unable to successfully complete this effort. This work is also dedicated to my parents, Forrest R. Hanvey Jr. and Suzanne M. Hanvey, in appreciation for the love for learning they instilled in me, and for teaching me to persevere.

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INTRODUCTION

Applications requiring SAW filters at high frequencies not attainable using conventional transducer structures and lithographic techniques have sparked considerable interest in alternative methods for achieving high frequency performance. Novel substrates and non-Rayleigh waves with relatively high acoustic velocities, combined with harmonic device operation, allow for a substantial increase in the practical SAW frequency range. However, even these approaches require the use of near-half-micron lithography at frequencies of 2.5 GHz and above. Creative transducer structures which increase the line widths to near one-half acoustic wavelength, such as the narrow gap transducer have been presented previously [1-6]. All of these structures require fabrication techniques which present considerable manufacturing challenges compared to standard SAW device fabrication processes. However, the high operating frequencies attained using such structures make the development of highly manufacturable half-wavelength transducer structures a promising approach for extending the frequency range of SAW device operation.

Low-loss SAW devices are required for certain applications where system noise figure or dynamic range cannot accommodate the higher loss typical of bi-directional SAW filters. Low-loss filters can be designed which retain the inherent advantages of

bi-directional filters, while providing low loss and excellent triple transit suppression. SAW filters using unidirectional transducers can be designed with fractional bandwidths of 0.1% up to approximately 15%, and with losses typically ranging from 2 dB to 12 dB [5, 7-20]. Low loss, narrow fractional bandwidth, and small size requirements can often be satisfied by multi-pole SAW resonator filters. Single pole resonators can be designed with fractional bandwidths of up to roughly 0.1%, and multi-pole resonator filters can typically be designed with fractional bandwidths of up to 0.4%. These devices generally have insertion losses of less than 10 dB and often less than 5 dB [7, 8, 21-23]. Additional techniques for achieving low-loss performance have been demonstrated, including multi-track transducer structures such as the interdigitated interdigital transducer (IIDT), ladder-type resonator filters, and transversely coupled resonator filters. These techniques are capable of producing losses in the 2 to 13 dB range [7, 8, 24-28].

This work describes the development and implementation of a multilevel, half-wavelength transducer structure for high frequency SAW device fabrication. Production of this transducer configuration requires only conventional SAW fabrication techniques, making it inherently more manufacturable than previously presented quasi-half-wavelength structures. One method for fabricating these devices requires no critical mask alignment steps, further enhancing manufacturability. This multilevel transducer structure is not inherently lossy, and therefore has the capability of operating with low loss. Any device configuration commonly used to achieve low-loss performance, such as the GUDT, IIDT, and others discussed above can potentially be implemented using this type of transducer.

CHAPTER 1

TRANSDUCER STRUCTURES FOR HIGH FREQUENCY SAW APPLICATIONS

Narrow Gap Transducers

Background

The narrow gap transducer in various forms [1-6] has been shown to generate SAW responses at frequencies of up to 17 GHz [3]. Thus, the development of highly manufacturable half-wavelength transducer structures shows promise for extending the frequency range of SAW device operation. Prior narrow gap transducers utilized either air gaps between the fingers or relied on thin oxide interfaces created by anodic oxidation of the electrode metal or a similar technique to separate electrodes of opposite polarity.

Air-Gap Transducers

Narrow gap transducers utilizing air gaps between the electrodes generally require very fine control of the photoresist side wall configuration during photolithography. In a typical narrow gap process, the first level metal pattern of half-wavelength electrodes is deposited in the standard manner. In order to allow the metal to leave a narrow gap, the resist side wall must be slightly retrograde, and a highly directional metal deposition

technique, such as evaporation, must be used. While this retrograde side wall effect can be obtained by treating certain resists chemically, such as soaking the resist in chlorobenzene to cause "mushrooming", the exact extent of the side wall undercutting and its uniformity will determine the size and uniformity of the gap width. These parameters are substantially harder to control than the standard photolithographic processes utilized in conventional one-level SAW device manufacturing, and are also more difficult to control than the manufacturing process required by the multilevel transducer structure discussed in the current work. Another air gap transducer fabrication process developed by the Solid State Devices and Systems Laboratory (SSDSL) of the University of Central Florida (UCF) [29] and utilized in this work avoids some of the concerns associated with photoresist side wall profile uniformity. This process, which is described in detail in Appendix A, completely avoids critical alignment steps, but requires back-side exposure of the wafer, a step generally not required in standard SAW device fabrication processes.

Anodic Oxidation Transducers

An alternative to the air gap is the metal oxide insulating gap, which has been demonstrated by Yamanouchi et al. [1, 3, 6]. Such gaps can be fabricated by depositing and patterning the first level metal, using anodic oxidation to selectively oxidize the surface of the first level metal, and then depositing metal between the existing electrodes. Such a technique provides much more control over gap width and uniformity than the air gap approach, but there are some manufacturing complications relative to conventional

SAW device fabrication processes. The selective oxidation process requires appropriately powered electrical connections to the devices during the oxidation process, and requires the submersion of the devices in solutions containing chemicals such as sulfuric acid, or ammonium tetraborate in ethylene glycol [1].

Combination Transducers

Certain narrow gap transducer structures utilize a combination of air-gap, dielectric, and metal oxide insulating layers to separate consecutive metal depositions. Recent work by Meguro et al. [5] has demonstrated a wide band filter with fundamental frequency of 5 GHz which utilizes both anodic oxidation or dielectric insulating layers and air gaps. The air gaps in this structure are formed by using highly directional deposition of metals at an oblique angle, which prevents deposition of metal in the shadows of existing metal or photoresist regions. In general, because oblique directional deposition of metals is possible in only one direction at a time, this technique must be combined with the use of an insulating layer to realize devices and avoid shorting between layers. While the results obtained are impressive, the processing issues associated with anodic oxidation and oblique directional metal deposition are non-trivial, and may lead to problems in manufacturing.

Multilevel Transducers

Introduction

This work describes the development of a multilevel, half-wavelength transducer structure for high frequency SAW device fabrication which utilizes conventional manufacturing processes. This transducer has several desirable characteristics, including the lack of reflections internal to the transducer, enhanced harmonic performance, and the ability to adjust the transducer impedance by altering the component layer characteristics. Unlike the narrow gap structure using either air gaps or anodic oxidation, production of this transducer configuration requires only conventional SAW fabrication techniques. Also, one version of the fabrication process presented here can be accomplished without any critical alignment steps, and is inherently more manufacturable than previously presented quasi-half-wavelength structures.

Transducer Structure

Two possible implementations of the multilevel transducer structure are shown in Figure 1 and Figure 2. In both cases, the first level metallization pattern consists of a bus bar connected to half-wavelength wide electrodes separated by half-wavelength wide spaces. On top of this first level metallization pattern is a dielectric insulating layer, such as the Si_3N_4 used in this work, which prevents shorting of the upper and lower metallization layers. The upper level consists of a metallization pattern complementary to the first level metal.

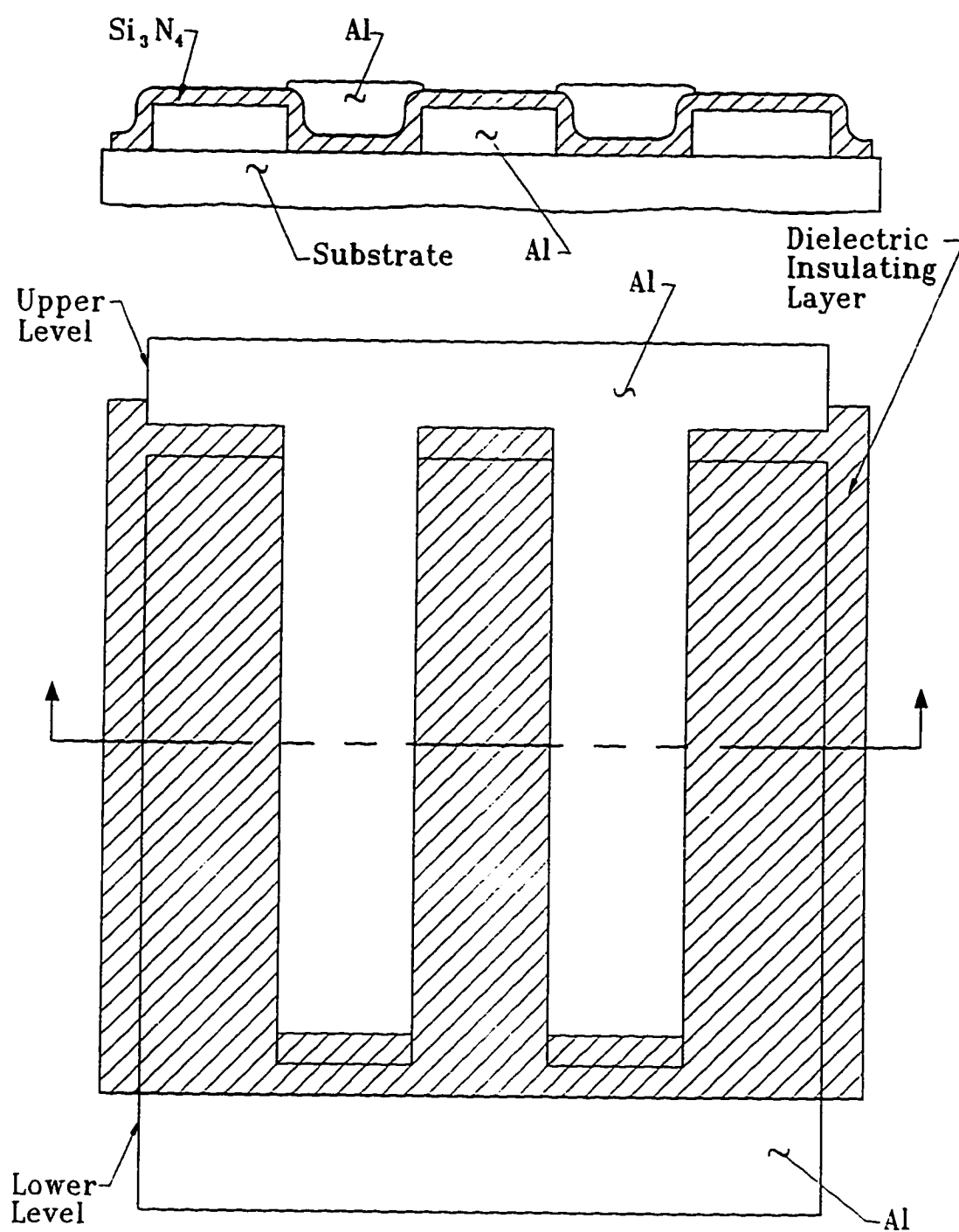


Figure 1. Multilevel transducer with interleaved upper and lower metal electrodes.

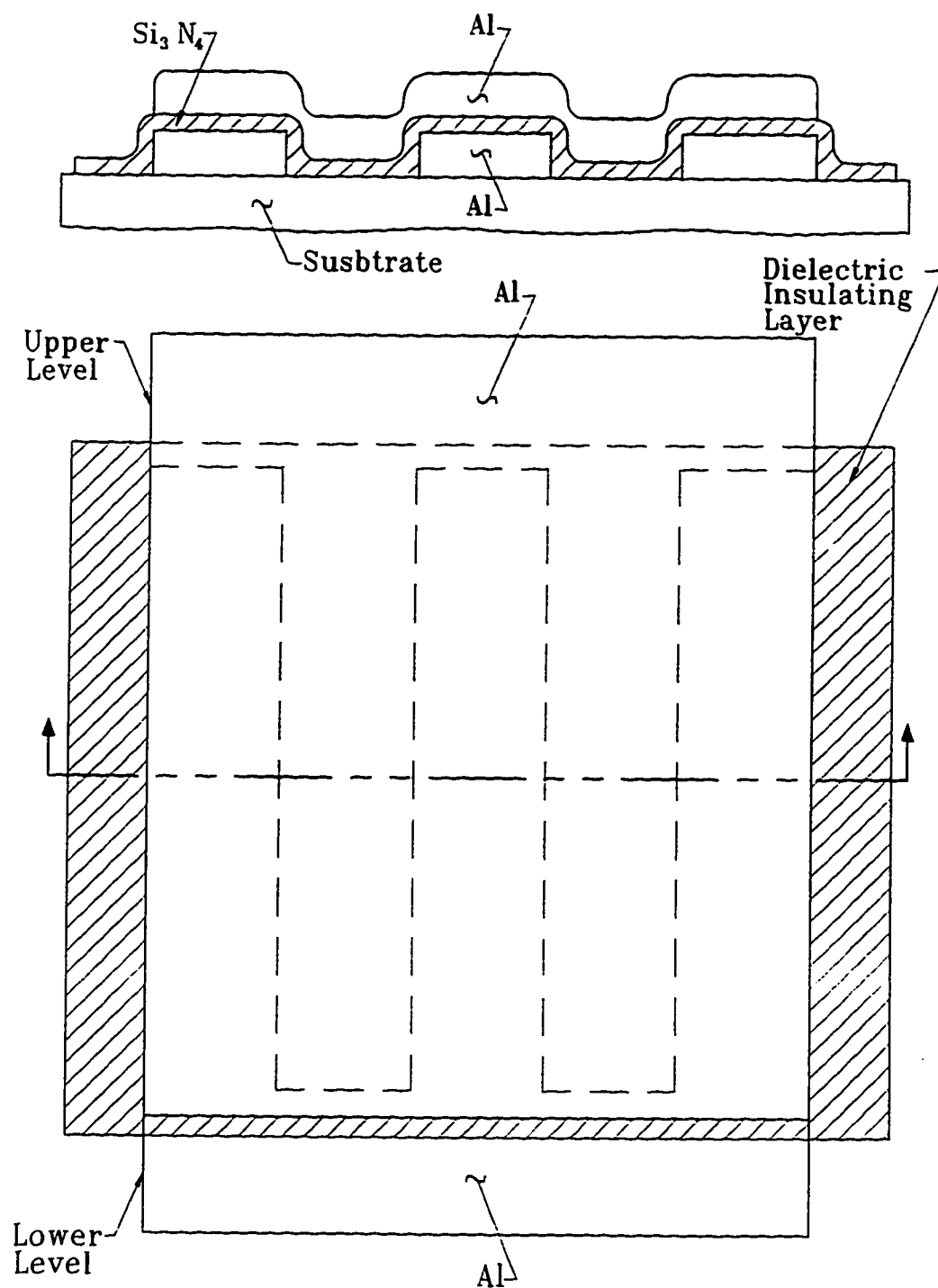


Figure 2. Multilevel transducer structure where upper electrode consists of a solid metal pad, rather than individual fingers.

As shown in Figure 1, the upper level metal can consist of a bus bar and connected half-wavelength electrodes, similar to the first level metal. These electrodes are horizontally aligned with the spaces between the electrodes on the first level metallization pattern. If desired, these electrodes can be slightly over-sized to reduce the requirement for precise alignment. Alternatively, these electrodes can be fabricated using backside exposure to completely eliminate the need for alignment. Backside exposure can also produce narrow gaps between electrodes, depending on the precise photolithographic process used.

Another option is to use a solid metal pad as the upper electrode, as shown in Figure 2. Once again, this alleviates the need for precise alignment, although the added transducer capacitance does produce a different unmatched device insertion loss, and the solid upper electrode enhances RF feedthrough and causes substantial distortion of the passband from the interdigitated response.

Fabrication Techniques

Devices were fabricated in this work using both a narrow gap multilevel transducer fabrication procedure and a multilevel transducer fabrication procedure which does not utilize narrow gaps. These procedures are discussed in Appendix A and Appendix B, respectively. In both procedures, YZ LiNbO₃ wafers with a diameter of 3 inches were coated with 900 to 1500 Å of aluminum, then patterned with the first level metal geometry using conventional photolithographic and wet etch techniques. After removing all photoresist, silicon nitride insulating films were deposited over the patterned

wafers in a modified Plasma Technology reactive ion etch (RIE) system (Model RIE-80), configured for plasma enhanced chemical vapor deposition (PECVD), using a combination of silane and ammonia. Details of the deposition technique are discussed in Appendix C, and the effects of variation in deposition conditions on film quality and composition are discussed in Chapter 2.

Standard photolithographic techniques were used to define a photoresist mask for reactive ion etching (RIE) of the Si_3N_4 . Hexamethyldisilazane (HMDS) was used to enhance adhesion of the photoresist to the nitride film during this step. The films used in this study showed an etch rate of 18 Å/sec in an 8.5% O_2 in CF_4 plasma with a gas flow rate of 100 sccm, RF power of 50 Watts, pre-plasma pressure of 250 mTorr, and with sample temperature maintained at 25 °C. Following reactive ion etching of the nitride pattern, the photoresist was stripped and an O_2 plasma clean was performed to remove remaining residue.

In the narrow gap process, the top level metal patterns were to be formed by a novel liftoff process which requires image reversal. Hoescht-Celanese AZ-5214, a dual-tone resist, was used for this process, and HMDS was once again used to enhance adhesion of the photoresist to the nitride film. Exposure of AZ-5214 catalyzes the formation of acidic compounds in the resist, which will cause the exposed resist to develop away if placed into AZ developer, a highly basic solution. However, this resist contains heat activated inhibitors, which neutralize the acidic compounds in exposed photoresist, stabilizing it and preventing the resist from developing away. This property allows for use of an image reversal process with an initial masked exposure, image reversal bake, and a

backside flood exposure. The first level metal pattern acts as a mask for the photoresist during the flood exposure, completely avoiding critical alignment steps. The narrow gap multilevel transducer fabrication process is described in detail in Appendix A.

In the alternative multilevel transducer fabrication process, following the RIE process the wafers were coated with Futurrex NR8-1000 photoresist, and were aligned and exposed from the top using either a coarse mask to define solid upper electrode pads or a mask with interdigitated upper electrodes requiring more careful alignment. This fabrication process flow is described in detail in Appendix B.

In either fabrication process, following the appropriate photoresist development and bake steps, a layer of aluminum approximately equal in thickness to the first layer was deposited using e-beam evaporation. Details of the evaporation process are given in Appendix D. Liftoff was then performed using slight agitation in acetone.

CHAPTER 2

STUDIES OF PECVD SILICON NITRIDE FILM DEPOSITION ON LiNbO_3

Introduction

Silicon nitride (Si_3N_4) prepared by low temperature plasma enhanced chemical vapor deposition (PECVD) is one of a group of thin film dielectrics which has found wide application in semiconductor devices and circuits, and in the integration of acoustic wave devices on semiconducting substrates [30-32]. Such dielectric thin films can also be useful when incorporated into SAW devices on traditional piezoelectric substrates such as lithium niobate (LiNbO_3). When properly configured, such layers can be used to provide various functions including device passivation, waveguiding, and reflective structures. Because of its high dielectric constant and density, silicon nitride was selected for use as the intermediate dielectric layer in the multilevel transducer structures described in Chapter 1.

The acoustic properties of amorphous Si_3N_4 formed by PECVD are determined by the film density, composition, and elastic constants. These quantities vary with the deposition parameters, which in the case of a parallel plate system include substrate temperature, pressure, RF power, electrode spacing, and flow ratios of the reactant gases. All of these parameters substantially affect the deposition and etch rates and other physical

and optical properties of the film. In previous work [33-36], a deposition parameter matrix was constructed for a $\text{SiH}_4\text{-NH}_3$ PECVD process, and the effects of variation of the above parameters on the deposition and etch rates were studied. A set of deposition parameters which result in high quality films useful for SAW devices were determined. In the current work, this set of parameters was verified, and the density, composition, and acoustic properties of Si_3N_4 films deposited on LiNbO_3 under these conditions were investigated. Acoustic properties such as propagation loss, velocity dispersion, and reflectivity were evaluated using SAW devices fabricated with silicon nitride film pads and reflective strip arrays between two unweighted transducers as test structures.

Film Deposition Conditions

The silicon nitride films were grown in a Plasma Technology reactive ion etch (RIE) system (Model RIE-80) modified for plasma enhanced chemical vapor deposition (PECVD). When configured for PECVD, this system is a parallel plate reactor with a mechanical pump for roughing and a molecular drag pump able to provide a background pressure of 2×10^{-5} Torr in the chamber prior to flowing the process gases. A detailed description of this system and the ancillary gas systems can be found in Appendix C. The water cooled upper electrode plate uses a "shower head" assembly to uniformly distribute the process gases. The lower plate can be water cooled or heated with the substrate heater to 400 °C. When operated under optimal deposition conditions, this system can yield a 95% uniformity diameter of approximately 15 cm, allowing for the deposition of

Si_3N_4 films onto up to three 3 inch diameter wafers per deposition. The RF power is connected to the top plate.

Films were grown using combinations of silane (SiH_4) and ammonia (NH_3). Due to the pyrophoric nature of silane, a 3% silane in helium mixture was selected as the silicon reactant source. Detailed information on the gases and the gas supply system is given in Appendix C.

The substrates used for initial deposition characterization studies in previous and current work were n-type silicon (100) wafers. After obtaining the initial high vacuum, the throttling was adjusted to obtain the required pressure for deposition. The system was then purged with ammonia at this pressure so as to clean the system from any residual oxygen. Before introducing the silane, the plasma was established with ammonia and this plasma was continued for two to three minutes. The required deposition parameters were then adjusted and all the conditions were stabilized before the deposition was started. Details of the deposition procedure are discussed in Appendix C.

Previous work conducted at SSDSL [33-36] studied the deposition and etch rates of Si_3N_4 films with respect to variations in substrate temperature, chamber pressure, RF power, deposition time, electrode spacing, and flow ratio of silane to ammonia. The current work further evaluated and extended the results obtained thereby. The range of these parameter variations performed in [34] are listed in Table 1, and results of [34] which are pertinent to or were extended by the current work are summarized briefly herein for completeness. The wet etch rates were determined initially by etching the silicon nitride film with semiconductor grade buffered oxide etch (BOE, 13 NH_4F :2HF) 9:1

Table 1

Range of Deposition Parameters Evaluated

Parameter	Range Of Values
Silane/Ammonia Flow Ratio	0.01 - 1.00
Chamber Pressure, mTorr	100 - 1000
R.F. Power, Watts	40 - 150
Substrate Temperature, °C	30 - 350
Time, minutes	5 - 30
Electrode Spacing, mm (ES)	30 - 60

Note. Source [34]

diluted in water obtained premixed from Ashland Chemical Company. Following optimization of film deposition parameters for acoustic device applications, dry etch rates were evaluated using an RIE process with C_2F_6 or $CF_4/8.5\% O_2$ as reactant gases, and film compositions were studied using Auger spectroscopic analysis.

Evaluation of Film Deposition Results

Effect of Silane to Ammonia Flow Ratio

The silane to ammonia flow ratio is defined as the ratio of the flow rate of SiH_4 in sccm divided by the flow rate of NH_3 in sccm. The range of silane to ammonia flow ratios tested was from 0.01 to 1.0. Figure 3 shows the variation of deposition rate with respect to an increasing gas flow ratio of SiH_4/NH_3 for two pressures (300 and 700 mTorr). The RF power and the substrate temperature were kept constant at 100 Watts and 300 °C. At

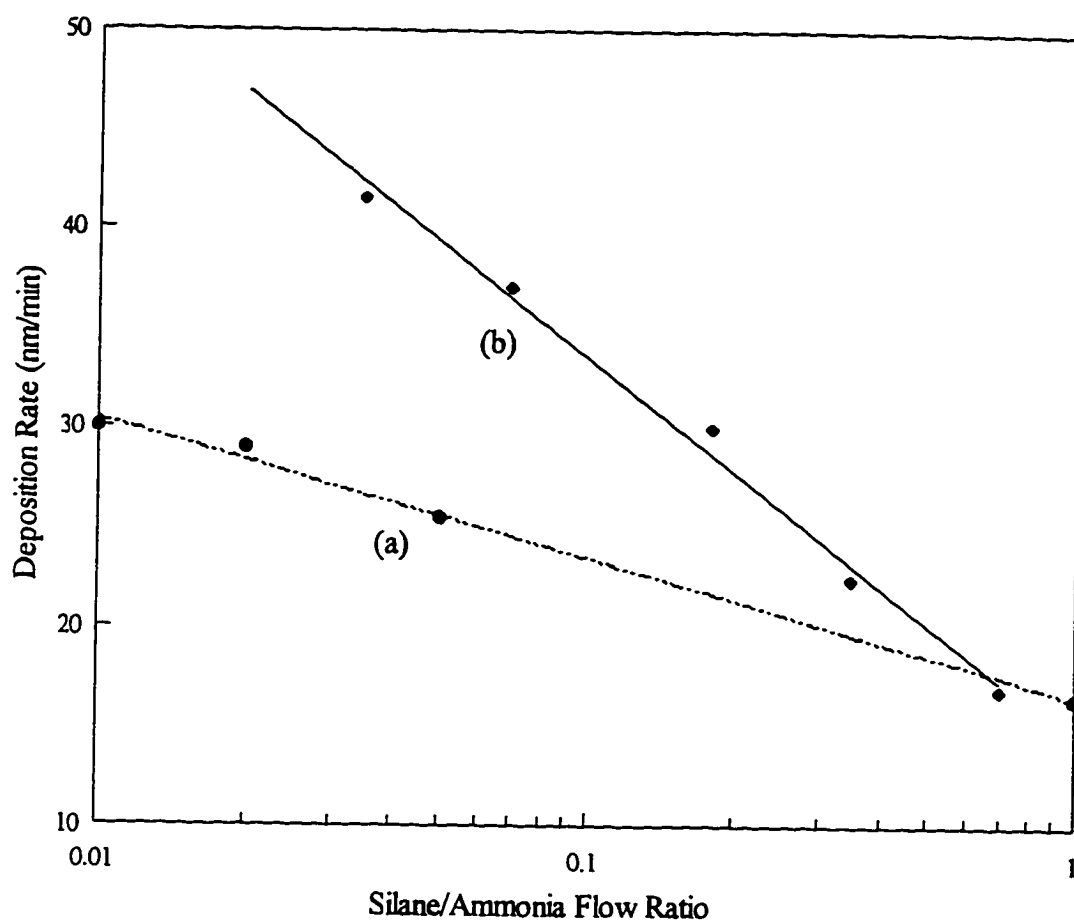


Figure 3. Deposition rate vs. SiH_4/NH_3 flow ratio. (a) Pressure = 300 mTorr, Time = 5 min., Electrode spacing = 56 mm. (b) Pressure = 700 mTorr, Time = 5 min., Electrode spacing = 58 mm. For both curves, Power = 100 W and Temp. = 300 °C [34].

a flow ratio of 0.5, the deposition rates have values similar to those reported by Sinha, et al. [37] and a higher deposition rate is observed at higher chamber pressure. The deposition rate slowly decreases when the flow ratio is increased. This is contrary to the results reported by Sinha, et al. and Piccirillo and Gobbi, where it is reported that as the

flow ratio increases the deposition rate also increases [37, 38]. However, Piccirillo's measurements of deposition rate versus flow ratio were performed at an RF power of 20 Watts, well below the power at which minimum deposition rate occurs. Osenbach, et al. while examining the flow ratio range between 0.2-2.0 found that the deposition rate increased initially, reaching a maximum value at approximately 0.4, and then decreased [39]. This was postulated to be the result of either a variation in conversion efficiency of the SiH_4 in the plasma or competing absorption-desorption surface reactions impeding film growth rates at flow ratios below 0.4 [39]. These depositions were conducted at 360 °C using 200 Watts of RF power at 440 kHz in a horizontal tube reactor.

In the present work, very small flow ratio experiments could not be performed because of the limitation of the flow meters and, for the given deposition conditions, the deposition rate showed a decreasing trend for an increase in flow ratio. Given the number of interacting factors involved in determining the deposition rate, these observations are not inconsistent with the findings of others [37-39].

Figure 4 shows the plots of the wet etch rate versus the flow ratio of silane to ammonia for films deposited with two different electrode spacings. Similar results were reported by other workers showing that the increase in flow ratio causes decrease in etch rate [37, 38, 40, 41]. This is due to the fact that the films deposited under high silane condition have more silicon and less hydrogen and nitrogen content in the film which decreases the etch rate [42]. The low etch rate observed at high flow ratios is also indicative of high density films.

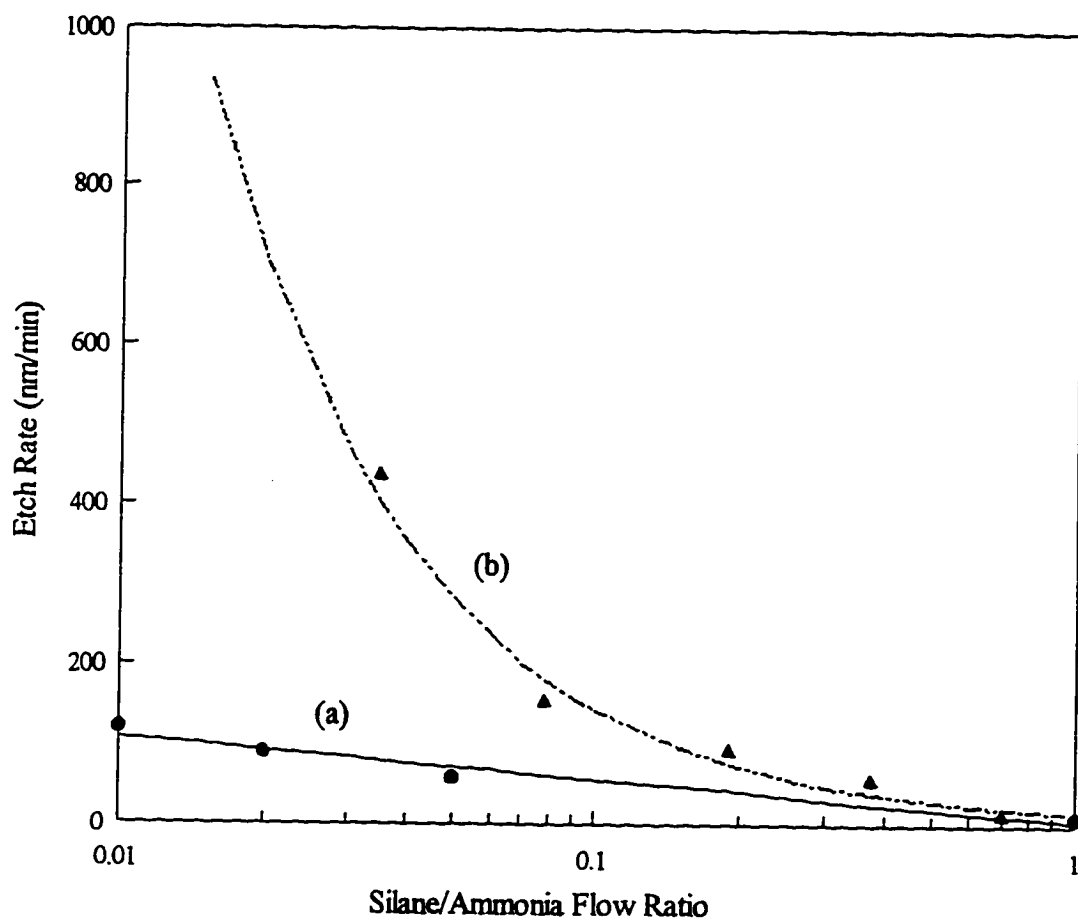


Figure 4. Wet etch rate vs. SiH_4/NH_3 flow ratio. (a) Pressure = 300 mTorr, Time = 5 min., Electrode spacing = 56 mm. (b) Pressure = 700 mTorr, Time = 5 min., Electrode spacing = 58 mm. For both curves, Power = 100 W and Temp. = 300 °C [34].

Effect of Pressure

The chamber pressure was varied from 200 to 1000 mTorr during deposition. Increases in the chamber pressure during film deposition caused both deposition rate and the subsequently measured wet etch rate to increase as shown in Figure 5. The increase in

pressure causes more ionized radicals in the processing ambient causing an increase in the deposition rate. The increase in deposition rate will, in turn, correspond to less dense films which can be etched faster, as observed by Sinha et al. and Hey et al. [37, 43]. As the density of the films decrease, acoustic losses tend to increase due to scattering caused by voids.

Effect of Power

The RF power was varied in the range of 10 to 200 Watts for depositions, which corresponds to varying power density from 22 mWatt/cm² to 440 mWatt/cm². Increasing RF power during deposition caused increases in both deposition and wet etch rate as shown in Figure 6. Similar results were reported by other workers [44, 45]. Sinha et al. found no critical change in density and etch rate with respect to increase in RF power, though deposition rate increased [37]. Piccirillo et al. observed a deposition rate with a strong RF power dependence which exhibited a minimum of slightly under 100 Å/min near 50 watts for a wide range of flow ratios. The deposition rate was observed to increase to over 200 Å/min for both higher and lower power levels. Piccirillo also observed a corresponding minimum in the etch rate, indicative of a decrease in film density with increasing deposition rate [38]. This minimum is not observed in the current work since no power levels considerably below 40 Watts were evaluated. Also, a slightly higher maximum power (200 Watts) is considered here, while Piccirillo maintained power at or below 150 Watts.

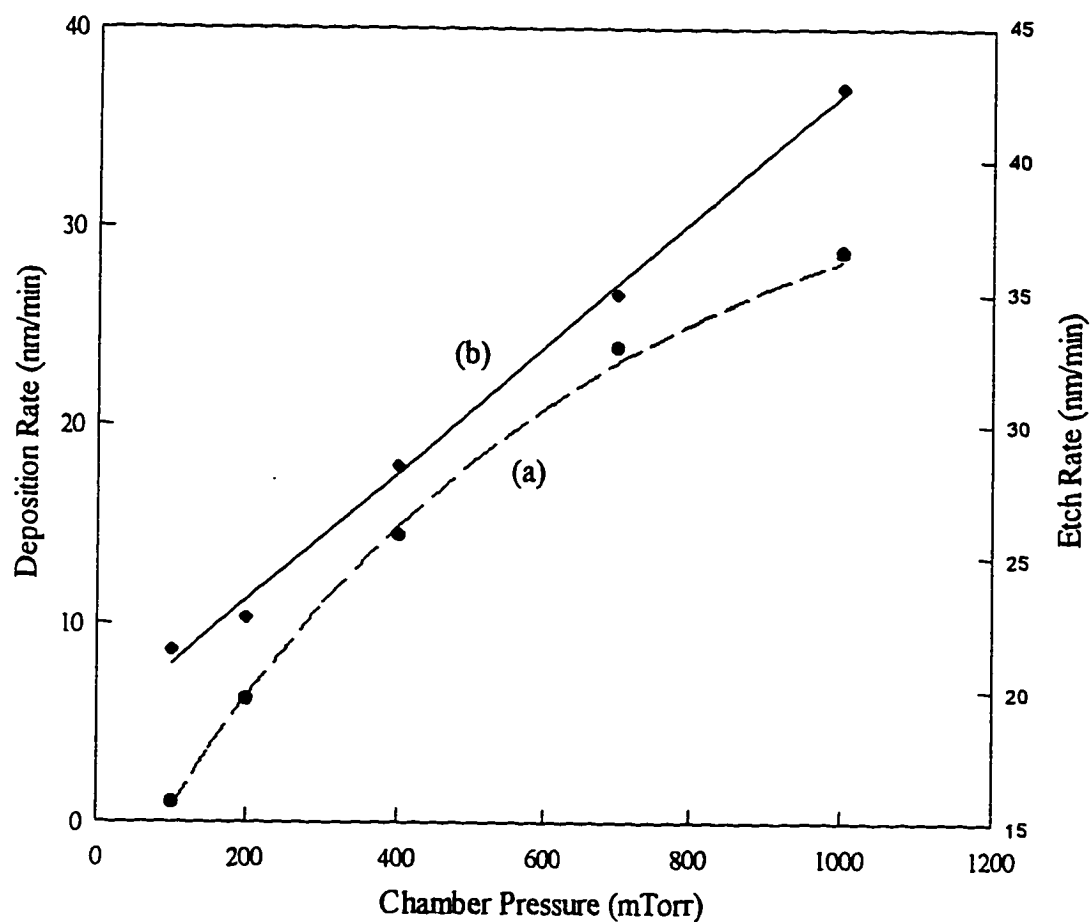


Figure 5. Deposition and wet etch rates vs. chamber pressure. Silane/ammonia flow ratio = 0.1, Power = 100 W, Electrode spacing = 56 mm, Temp. = 300 °C, Time = 5 min. (a) Deposition rate (nm/min), (b) Wet etch rate (nm/min) [34].

Effect of Substrate Temperature

The effect of substrate temperature on the deposited film was investigated by varying the temperature from room temperature to 350 °C, keeping the other parameters fixed. Figure 7 shows that as substrate temperature increased, the deposition rate

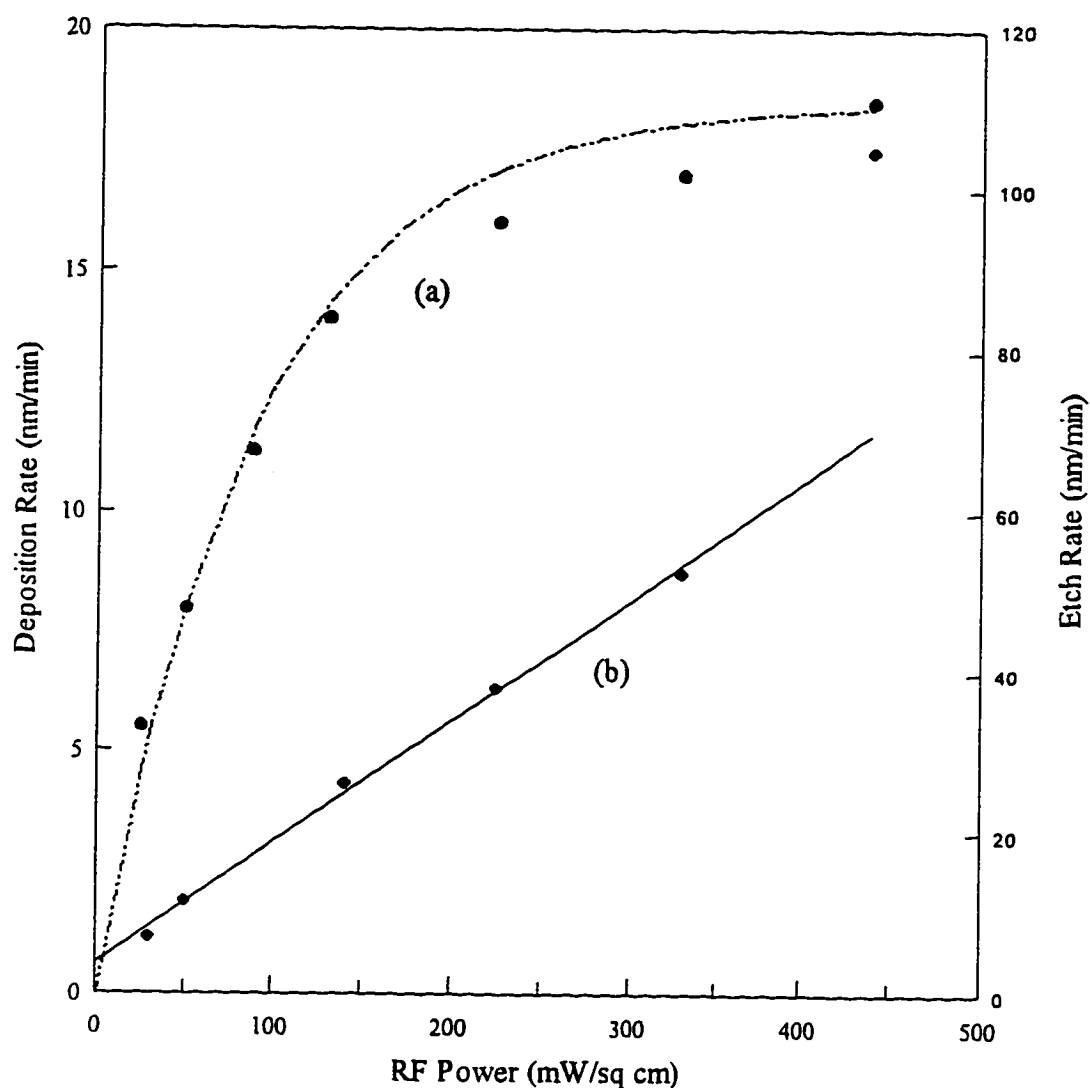


Figure 6. Deposition and wet etch rates vs. RF power. Silane/ammonia flow ratio = 0.01, Pressure = 400 mTorr, Electrode spacing = 57 mm, Temp. = 300 °C, Time = 10 min. (a) Deposition rate (nm/min), (b) Wet etch rate (nm/min) [34].

decreased. Rosler concluded that accurate temperature control is not very important in a CVD process activated not by temperature but by an RF glow discharge because it is

found that the deposition rate decreased by only 3% for every 50 °C increase in temperature [45, 46]. This is contrary to the current findings, where it is observed that deposition rate can decrease by up to 25% for a 50 °C increase in temperature. Figure 7 also shows the decrease in etch rate observed as deposition temperature increases, and similar results have been reported by other researchers [37, 38, 41].

Films produced at higher temperature will tend to have less hydrogen content, be more dense, and etch more slowly, all desirable film properties for SAW applications.

Effect of Electrode Spacing

The electrode spacing was varied between 25 mm and 58 mm for the silane-ammonia process. The behavior of the deposition rate is shown in Figure 8. The electrode spacing to achieve highest deposition rate for the stated deposition parameters is approximately 38 to 40 mm. Since the density of the deposited film is inversely related to deposition rate, the electrode spacing to achieve high quality films for acoustic applications under optimum SAW film deposition conditions was selected as 57 mm.

Optimum SAW Film Deposition Conditions

Silicon nitride films which are desirable for surface acoustic wave (SAW) device applications have densities nearing those of bulk Si_3N_4 , indicating high quality films with few voids. Such films result in high acoustic reflectivity, a large change in acoustic velocity due to stiffening of the surface of the piezoelectric substrate, and inherently low propagation loss under the film relative to other dielectrics. These effects allow for

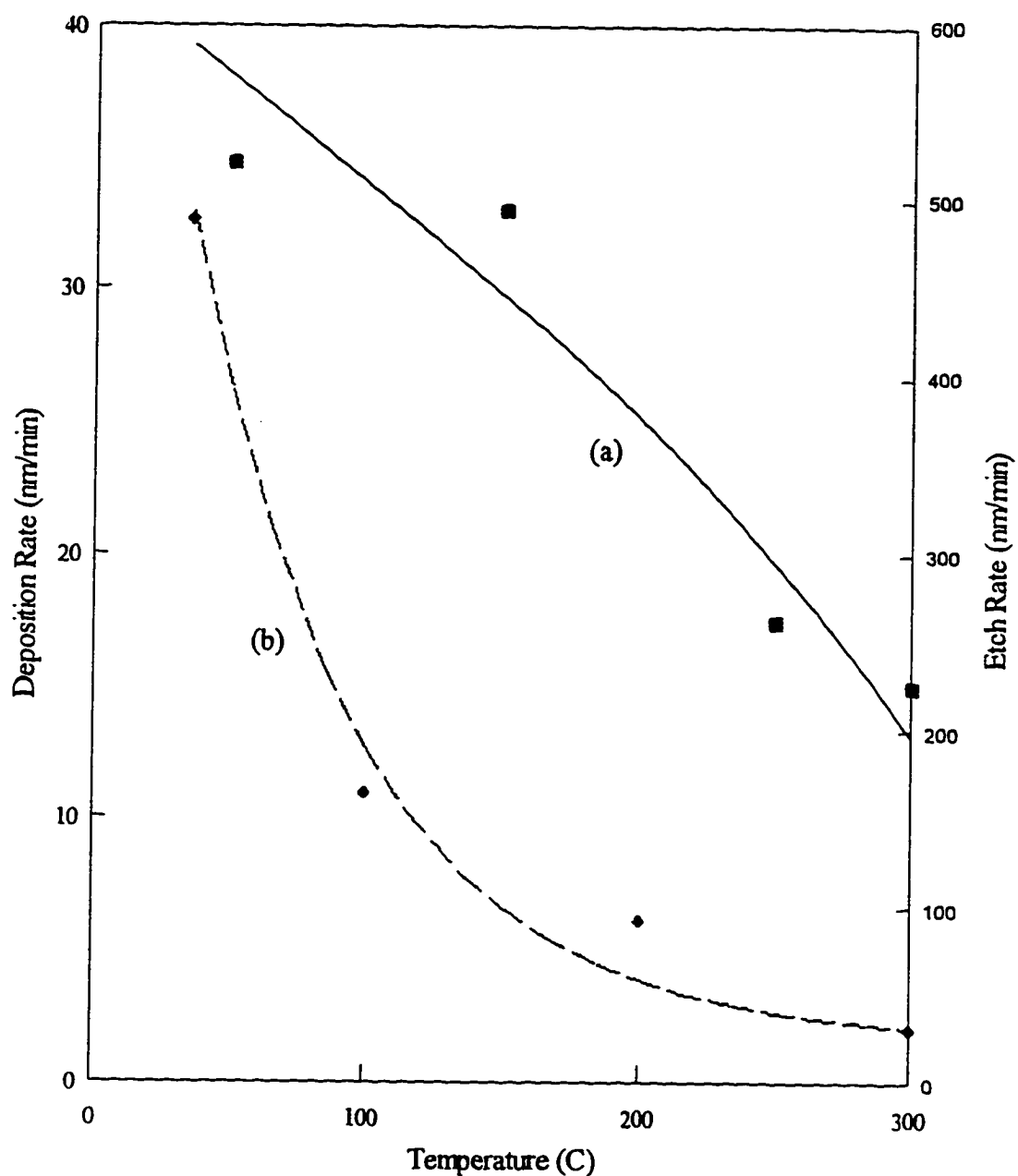


Figure 7. Deposition and wet etch rates vs. temperature. Silane/ammonia flow ratio = 0.05, Pressure = 200 mTorr, Power = 150 W, Electrode spacing = 57 mm, Time = 10 min. (a) Deposition rate (nm/min), (b) Wet etch rate (nm/min) [34].

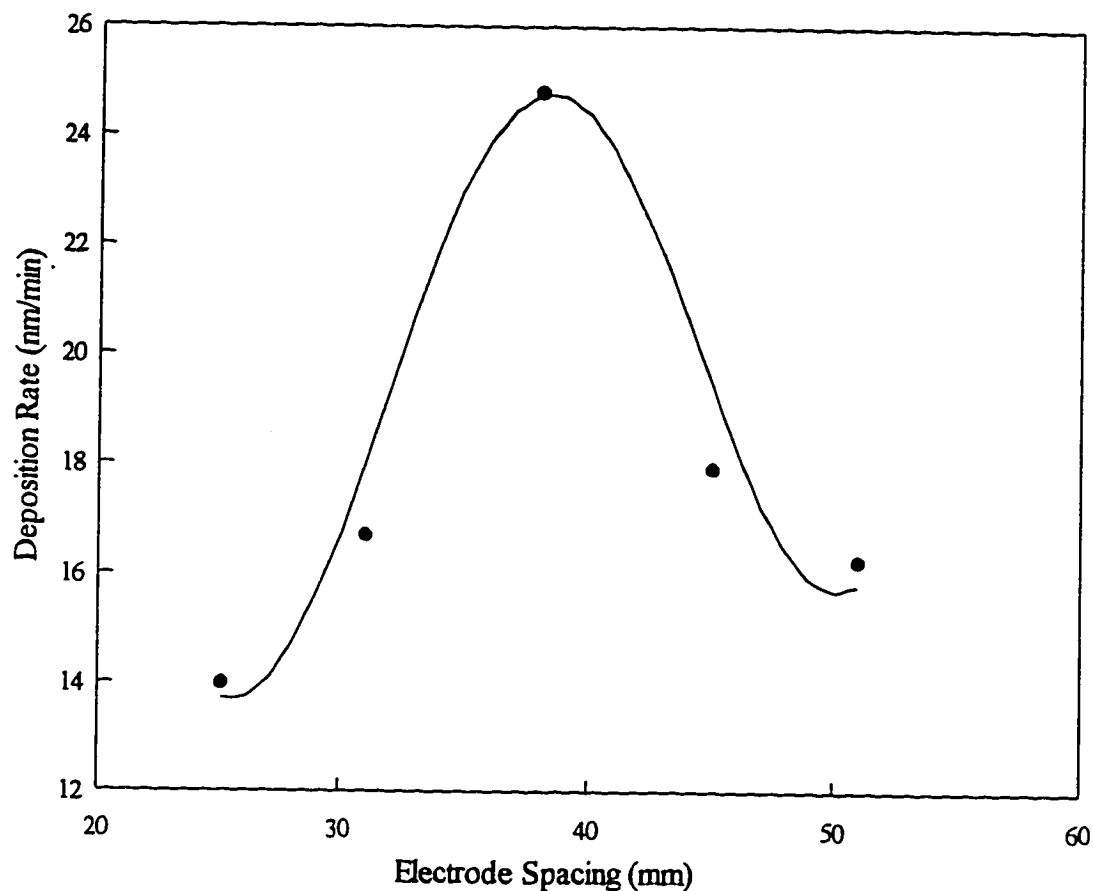


Figure 8. Deposition rate vs. electrode spacing. Silane/ammonia flow ratio = 0.5, Pressure = 200 mTorr, Power = 150 W, Temp. = 150 °C, Time = 10 min [34].

implementation of acoustic reflecting structures and waveguiding structures with thin nitride film thicknesses, further reducing acoustic losses due to presence of the film. In order to obtain dense, high quality films, it is necessary to deposit the films under conditions which limit the amount of hydrogen incorporated into the films, and allow for film growth at low deposition rates. Deposition conditions which yielded excellent film

properties for use in the acoustic devices under consideration were chosen from the range of deposition parameters described in Table 1 (Chapter 1).

The parameters which were found to be optimum for Si_3N_4 deposition for acoustic applications were used for the depositions in this work, and are summarized in Table 2.

Details of the deposition procedure are given in Appendix C.

Analytic Film Studies

The compositions of several films deposited under these conditions were evaluated using Auger electron spectroscopy and density comparisons, and were found to be close to the ideal Si_3N_4 [36]. Infra-red spectroscopy was also used for verification of film compositions. Wet and dry etch rates were evaluated for films deposited under the conditions specified above.

Films deposited under the optimized conditions described above were observed to have a wet etch rate of $22 \pm 7 \text{ \AA/min}$ in buffered oxide etch (BOE) at room temperature.

Table 2

Optimum Deposition Parameters

Parameter	Optimum Value
Power Density	663 mW/cm ²
RF Power	100 Watts
Electrode Spacing	57 mm
Pressure	700 mTorr
Temperature	300 °C
Gas Flow Ratio	$\text{SiH}_4/\text{NH}_3 = 0.705$

This slow etch rate is due to the high density of the films, calculated to be 2.96 ± 0.07 g/cm³, fairly close to the density of bulk Si₃N₄, 3.1 g/cm³. The film densities were calculated based on the measured mass of the nitride film of a known area. The mass measurement was performed by weighing large reference Si wafer pieces of known area which had been coated with Si₃N₄ at the same time as the devices, etching off the nitride layer, and repeating the weighing process. The slight decrease in density with increasing film thickness observed by Hickernell [32] was not seen for films with thicknesses between 800 Å and 3600 Å. It is well documented that silicon nitride films fabricated by low temperature PECVD using silane and ammonia are often high in hydrogen content [32, 38, 47, 48], resulting in variation in physical and chemical film properties. High densities imply low hydrogen content and stoichiometry nearing Si₃N₄. The density reported by Taylor for a film with the composition Si₃N₄ was 3.00 g/cm³ [48]. Interpolating Taylor's measured densities and stoichiometries, the measured densities for the films produced in the current work indicate that these films are approximately Si₃N_{3.898}.

The compositions of the films were analyzed using Auger electron spectroscopy (AES). The AES depth profiling of the films was done to a depth of 1500 Å by sputter etching the film and making a measurement every 100 Å. A typical AES depth profiling of the silicon nitride film is shown in Figure 9 indicating that the composition of the film was fairly uniform, with very low carbon and oxygen contents. An estimation of the average composition of the film based on AES spectra was found to be Si₃N_{3.886}O_{0.05}, in good agreement with the density-based estimate. Infra-red spectroscopic analysis confirmed the low hydrogen content of these films [49].

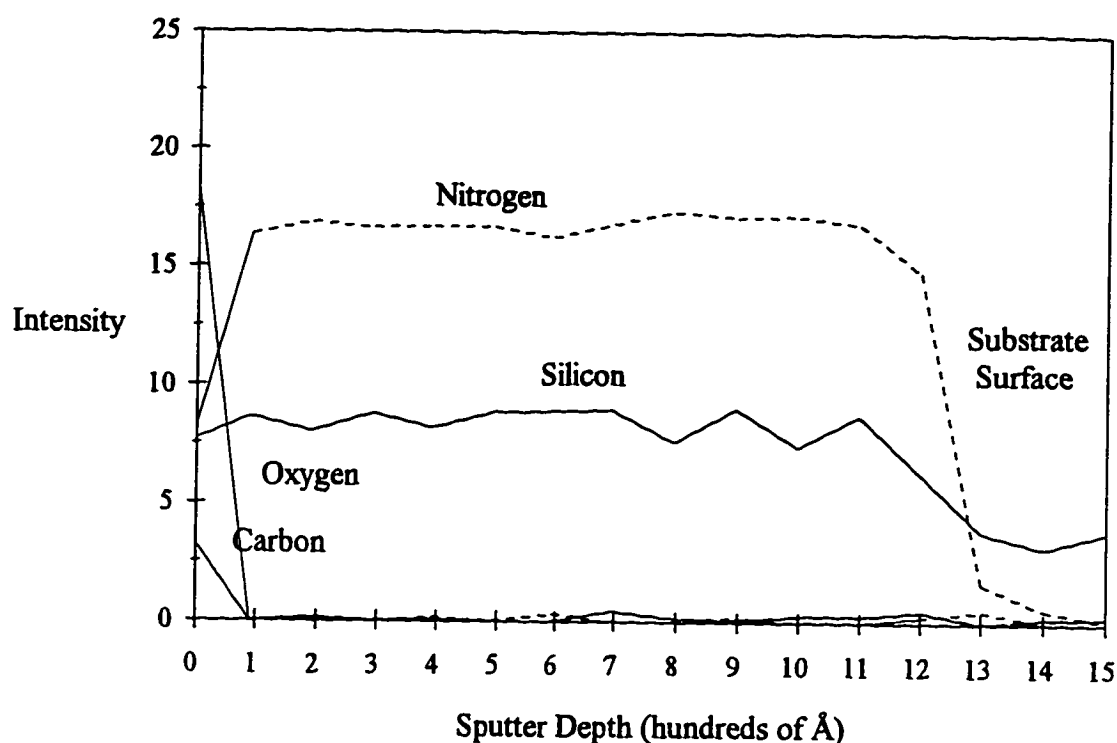


Figure 9. Auger Electron Spectroscopy (AES) depth profile of silicon nitride films. Data taken every 100 Å sputtering through film.

Because BOE can etch aluminum, a dry RIE process is preferable for etching the silicon nitride film pads required by the multilevel transducer structures described in Chapter 1. Dry etching of silicon nitride films deposited under optimized conditions was evaluated using a RIE process with a C_2F_6 plasma and using a RIE process with a $CF_4/8.5\% O_2$ plasma. The RIE processes used, along with process conditions and system operating procedures are described in detail in Appendix A. For etch times ranging from 30 seconds to 4 minutes, the films showed an etch rate in the C_2F_6 plasma of 6.34 Å/sec, with an offset of 45 Å as illustrated in Figure 10. In the RIE process utilizing an 8.5% O_2 in CF_4

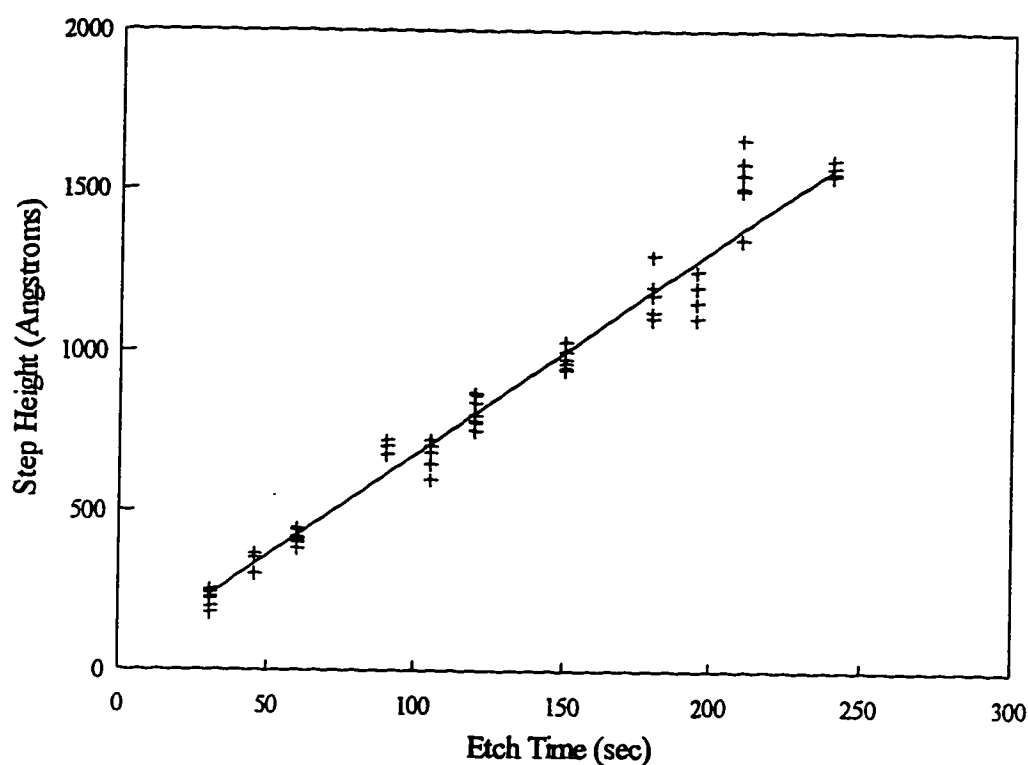


Figure 10. Dry etch rate in C_2F_6 of Si_3N_4 deposited under optimum PECVD conditions.

reactant gas mixture, with a gas flow rate of 100 sccm, RF power of 50 Watts, pre-plasma pressure of 250 mTorr, and with sample temperature maintained at approximately 25 °C by maintaining coolant flow to the bottom RIE electrode, the films showed an etch rate of approximately 18 Å/sec with an offset of -32 Å for etch times from 24 seconds to 54 seconds. Using a gas flow rate of 25 sccm, RF power of 100 Watts, and pre-plasma pressure of 55 mTorr resulted in a silicon nitride etch rate of approximately 25 Å/sec with an offset of -453 Å for etch times ranging from 30 seconds to 90 seconds. These etch rates are shown in Figure 11.

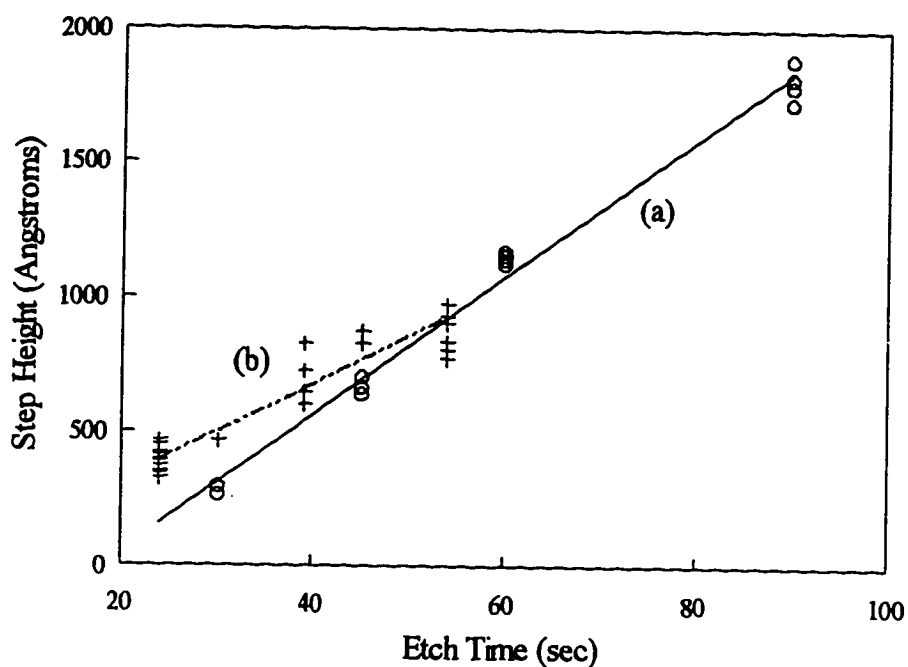


Figure 11. Dry etch rates in CF_4/O_2 of Si_3N_4 deposited on YZ LiNbO_3 under optimum PECVD conditions. (a) RF power = 100 Watts , (b) RF power = 50 Watts.

Deposition Rate Determination

Films were deposited with deposition times ranging from 3 minutes to 30 minutes which resulted in film thicknesses ranging from approximately 300 Å to 3600 Å. Patterns were generated in the silicon nitride films using standard photolithographic techniques and both wet and dry etching of the films. Film thickness measurements were made using an α -step profilometer. As shown in Figure 12, film thickness increased linearly with increasing deposition time. This data was taken from three independent deposition runs conducted in December 1993, April 1994, and May 1996. The system was converted from PECVD mode into RIE mode and back between each of these depositions runs.

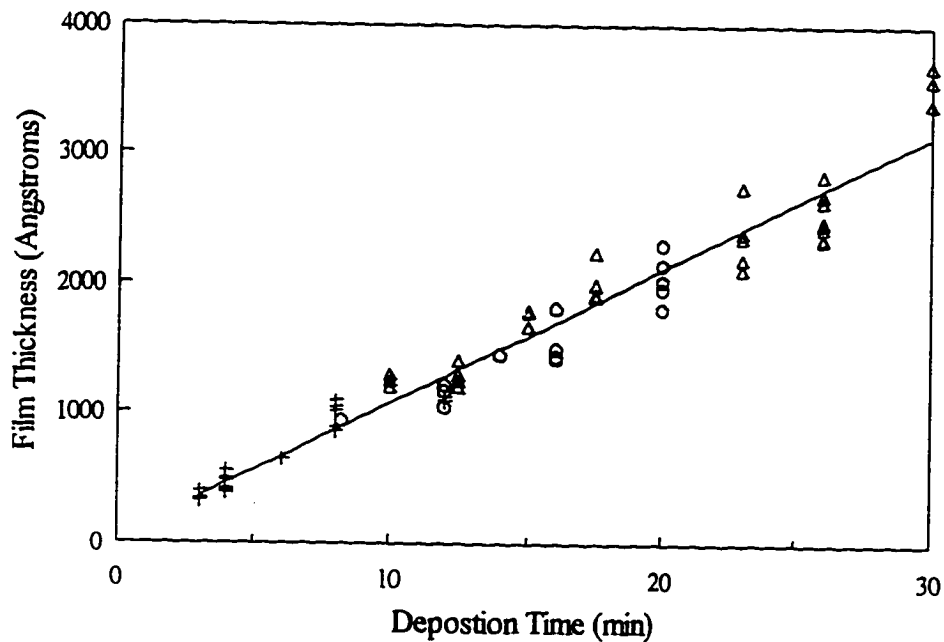


Figure 12. Deposition rate of Si_3N_4 deposited under optimum PECVD conditions.

Circles, triangles, and plus signs depict data taken from three separate deposition runs in December 1993, April 1994, and May 1996, respectively.

Note the high reproducibility of data, indicating long-term process stability and system reliability. From this data, the deposition rate with optimized deposition conditions averaged 103 Å/min for times over 3 minutes, with a 53 Å offset.

Summary

Silicon nitride films were deposited by a PECVD process using silane-ammonia as the reactant gas mixture. Both the deposition and wet etch rates of the films were found to be good indicators of film density and quality. By choosing the proper combination of

deposition parameters, it was possible to achieve the desired deposition and etch rate characteristics for films for SAW applications. The process parameters used for depositing high quality silicon nitride films for SAW applications were presented. This study has shown good correlation with previously published work and indicates that the potential exists for the growth of high quality PECVD silicon nitride films on many different types of SAW substrates.

CHAPTER 3

SAW TEST STRUCTURES AND PARAMETER EXTRACTION TECHNIQUES

Introduction

This chapter presents a simple technique for extracting fundamental SAW transducer equivalent circuit parameters from measurements easily performed on a network analyzer. This technique allows for the separation and unambiguous determination of basic equivalent circuit parameters such as parasitic (thin film) resistance, transducer capacitance, acoustic susceptance, and Hilbert Transform conductance. It is applicable to any transducer geometry, but is particularly useful in model development for unconventional transducer structures, such as the narrow gap and multilevel devices considered in the current work. In such cases, quantities such as transducer capacitance and effective coupling may not be easily calculated from previously known relationships.

Over the past twenty-five years, numerous variations of the Mason equivalent circuit for the in-line-field and the crossed-field approximations presented by Smith et. al. [50] have been used to model the behavior of many types of SAW devices. The current work utilizes one form of this equivalent circuit model as an analytical and predictive tool for determining the effective material parameters for standard and unconventional transducer structures, and for simulating approximate device performance.

Equivalent Circuit Configurations

The basic equivalent circuit used in this work in the parallel form consists of the conventional terms for transducer capacitance (C_t), two terms which represent acoustic wave excitation, the acoustic conductance $G_a(\omega)$ and the acoustic susceptance $B_a(\omega)$, and an additional series resistance which represents the parasitic thin film resistance (R_t). As used here for parameter extraction, these lumped elements approximate the performance of the entire transducer. As usual, the electrical behavior of this circuit can be represented by either the series or the shunt version of the circuit shown in Figure 13. Generally, the modified crossed-field model used to represent the performance of a surface wave device is best represented by the shunt circuit [51, 52]. These two descriptions are equivalent, however, and throughout the equivalent parameter extraction process, we will convert back and forth from the series to the parallel equivalent circuit, as necessary to facilitate our calculations.

The input impedance of the series equivalent circuit shown in Figure 13 (a) can be written

$$Z = R_t + Z_a(\omega) \quad (1)$$

where R_t is the transducer parasitic electrode resistance, and $Z_a(\omega)$ represents the acoustic impedance of the transducer, given by

$$Z_a(\omega) = R_a(\omega) + j(X_a(\omega) + X_t(\omega)) \quad (2)$$

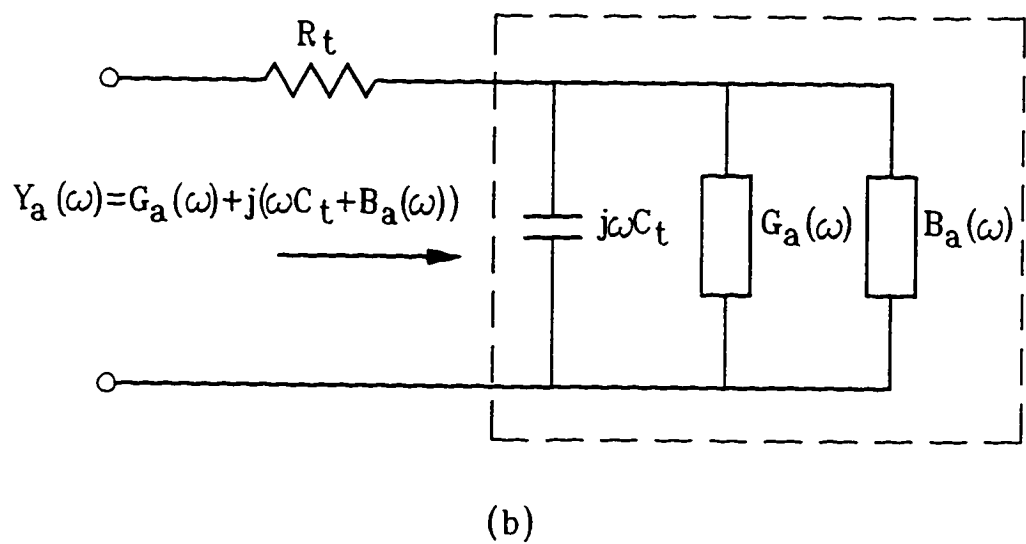
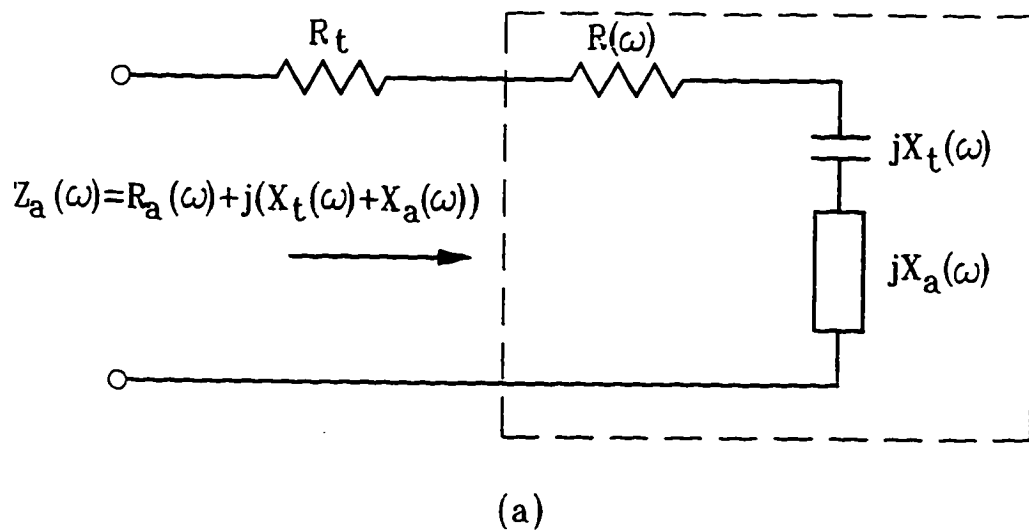


Figure 13. SAW equivalent circuit models. (a) Series equivalent circuit, (b) Parallel equivalent circuit.

In equation (2), $R_a(\omega)$ represents the acoustic resistance, and the total transducer reactance due to acoustic and capacitive effects is given by $(X_a(\omega) + X_t(\omega))$. The series input resistance and reactances are related to the acoustic conductance $G_a(\omega)$, the acoustic susceptance $B_a(\omega)$, and the transducer capacitance C_t by

$$R_a(\omega) = \frac{G_a(\omega)}{G_a^2(\omega) + (\omega C_t + B_a(\omega))^2} \quad (3)$$

$$X_a(\omega) = \frac{-B_a(\omega)}{G_a^2(\omega) + (\omega C_t + B_a(\omega))^2} \quad (4)$$

and

$$X_t(\omega) = \frac{-\omega C_t}{G_a^2(\omega) + (\omega C_t + B_a(\omega))^2} \quad (5)$$

For an unweighted transducer, the acoustic conductance can be written

$$G(\omega) = G_0 \left[\frac{\sin(X)}{X} \right]^2 \quad (6)$$

and the susceptance is given by

$$B_a(\omega) = G_0 \left[\frac{\sin(2X) - 2X}{2X^2} \right] \quad (7)$$

In the above equations,

$$X = \frac{N(f - f_0)}{f_0} \quad (8)$$

where f_0 is the center frequency and the ideal center frequency transducer conductance is

$$G_0 = 8k^2 C_s \gamma f_0 W N^2 = 8k^2 \left[\frac{C_t}{\zeta} \right] f_0 N \quad (9)$$

In equations (8) and (9), N represents the number of finger pairs, k^2 is the substrate piezoelectric coupling coefficient, γ is a constant that takes into account transducer finger structure ($\gamma = 1$ for non-split fingers, $\gamma = 1.414$ for split fingers), ζ is the ratio of normalized center frequency conductance relative to a non-split device ($\zeta=1.0836$ for a split finger transducer and $\zeta=1.0$ for a non-split transducer), W is the transducer aperture, and C_s is the capacitance per finger pair per unit length, also referred to by Datta as the substrate equivalent dielectric constant [53]. This implies the transducer capacitance can be written

$$C_t = \gamma N W C_s . \quad (10)$$

The admittance of the parallel equivalent circuit can be written as

$$Y(\omega) = \frac{1}{Z(\omega)} = \frac{1}{R_t + Z_a(\omega)} . \quad (11)$$

The transducer parasitic resistance term, however, complicates this expression relative to the acoustic admittance

$$Y_a(\omega) = \frac{1}{Z_a(\omega)} = G_a(\omega) + j(\omega C_t + B_a(\omega)) . \quad (12)$$

Parameter Extraction Technique

The basic equivalent circuit parameters for the model presented in Figure 13 can be found from simple S-parameter measurements. A full two-port calibration or two full one-port calibrations can be performed. Experimental results in the current work indicate

no measurable difference in the S_{11} and S_{22} magnitude and phase measured using these two calibration techniques, provided accurate calibration standards are used. Magnitude and phase data are collected for S_{11} and S_{22} over a span at least two to three times as wide as the null bandwidth of the filter. This S-parameter data is then converted to port input impedances using the relationship

$$Z_j = Z_{0j} \left[\frac{1 + S_{jj}}{1 - S_{jj}} \right] . \quad (13)$$

The transmission line characteristic impedance Z_{0j} used for these measurements was 50Ω . The real and imaginary portions of the input impedances for each transducer can then be found. Figure 14 illustrates the real part of the input impedance for a 60 MHz unweighted split-finger transducer with aperture $W = 55 \lambda$ and $N = 5$ built on 112° lithium tantalate. Although relatively accurate values were known for this substrate, this parameter extraction approach does not require any a-priori knowledge of the substrate constants C_s and k^2 . These values, along with velocity, can easily be determined from measurements provided the geometry of the device is known. For apodized devices, this approach strictly yields accurate results only at center frequency. In this case, N would be replaced by N_{eff} , a value which can be determined by matching the null bandwidth of an ideal unweighted transducer with measured data.

The transducer parasitic resistance R_t in equation (1) can easily be found as the constant offset in the real part of Z as shown in Figure 14 [54], and subtracted from the transducer input impedance, yielding $Z_a(\omega)$. This acoustic impedance can then be inverted

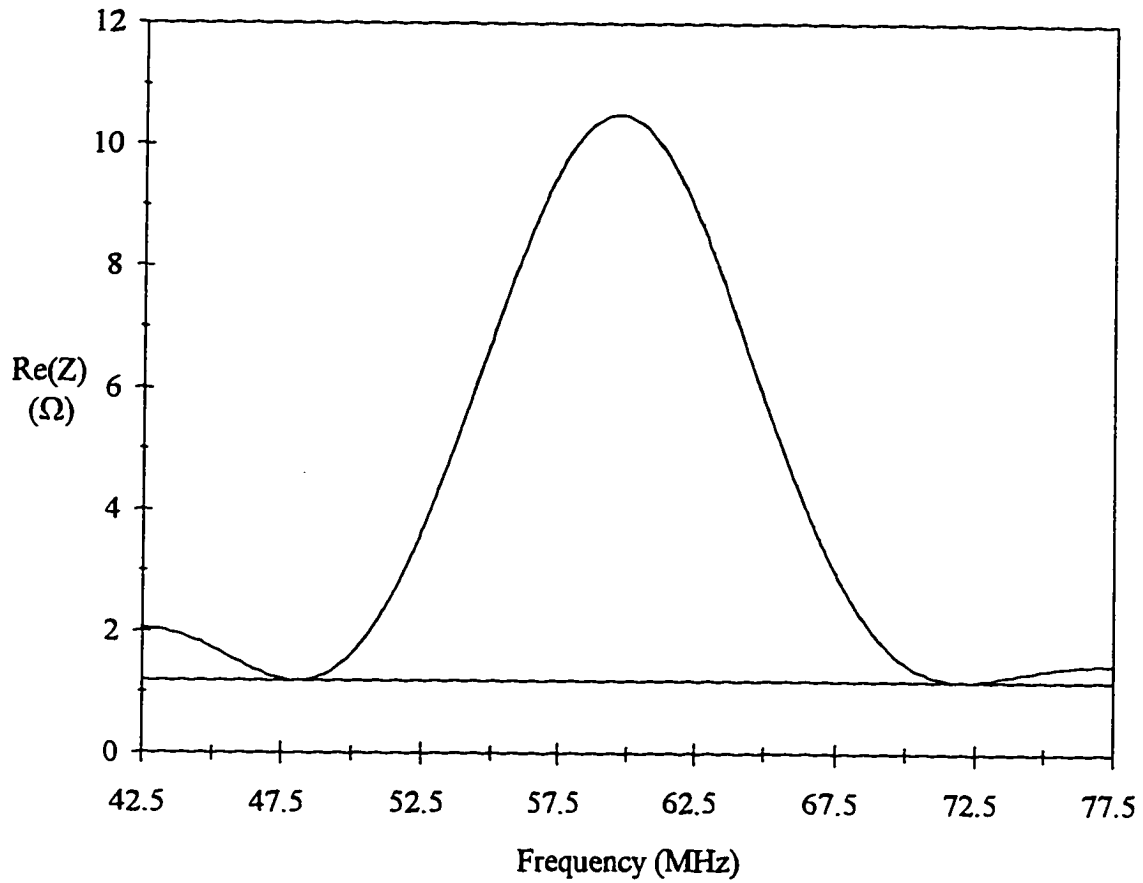


Figure 14. Transducer parasitic resistance extraction. Solid curve illustrates the real part of the input impedance for a 60 MHz unweighted split-finger transducer with aperture $W = 55 \lambda$ and $N = 5$ built on 112° lithium tantalate. $R_i = 1.203 \Omega$, the constant offset.

to yield the acoustic input admittance $Y_i(\omega)$. A linear fit to the values of $\text{Im}(Y_i(\omega))$ in frequency ranges away from device center frequency can be used to extract the total measured capacitance C_{meas} as shown in Figure 15. This measured capacitance is the sum of the transducer and bond pad capacitances. Header capacitance was calibrated out by

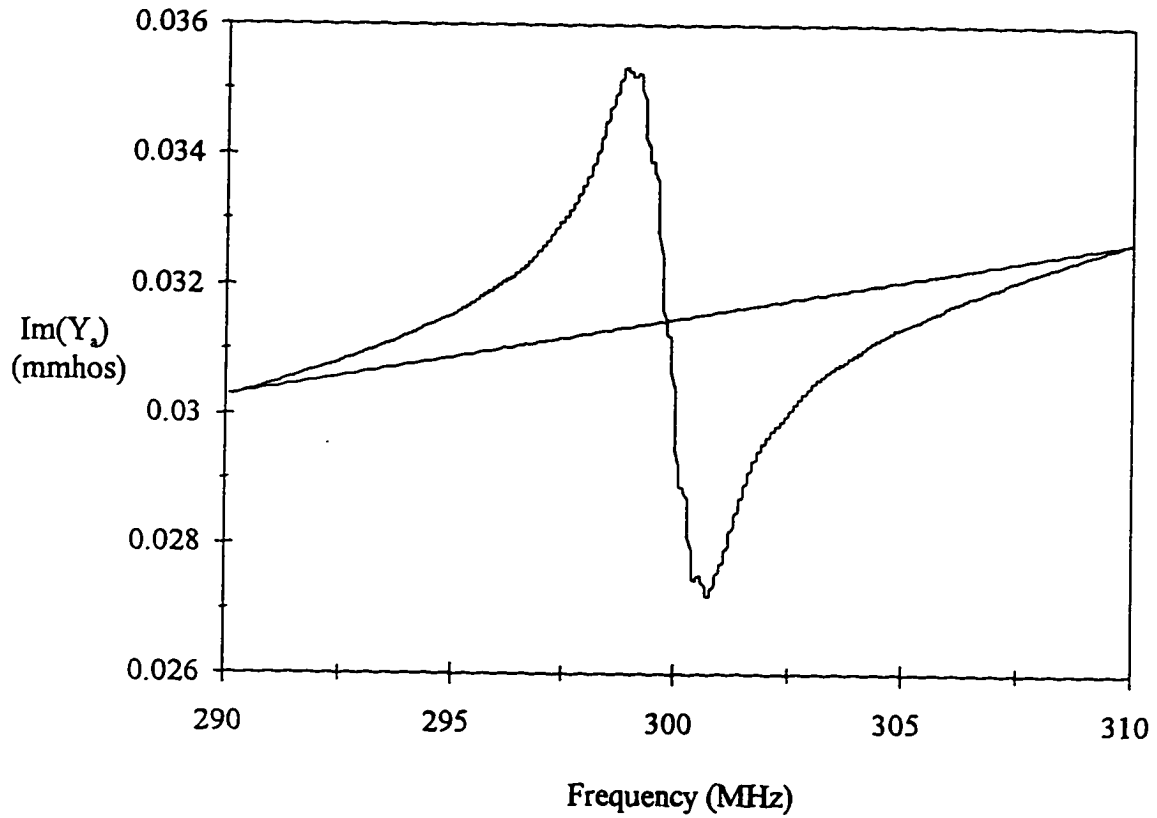


Figure 15. Total capacitance extraction. Solid curve illustrates the imaginary part of the input admittance for a 300 MHz apodized split-finger transducer with aperture $W = 165 \lambda$ built on ST quartz. Slope of the linear fit $= \omega C_{meas}$.

performing the calibration up to the header pins or pads. Bond pad capacitance depends on the bond pad area and the substrate effective dielectric constant C_s . If C_s is initially unknown, an effective value can be obtained using

$$C_s^{eff} = \frac{C_{meas}}{\gamma NW + \left(\frac{A_{pads}}{h} \right)} \quad (14)$$

where A_{pads} is the total bond pad area on the transducer and h is the wafer thickness. This extracted value of substrate equivalent dielectric constant is an effective value which incorporates the effects of the actual transducer structure, including properties of layers used in multilevel transducers and the effects of varying transducer metallization ratio. If extraction is performed on a single level conventional SAW transducer with 50% metallization, then C_s^{eff} is equivalent to C_s , the substrate equivalent dielectric constant. The extracted effective value C_s^{eff} can be used in place of C_s in equation (10) to calculate transducer capacitance C_t .

Once C_s^{eff} and C_t have been found, the experimental transducer acoustic Q (Q_t) can be used to find a value for k^2 . Q_t is related to C_t and the center frequency value of the acoustic conductance $G_a(\omega_c)$ by

$$Q_t = \frac{\omega_c C_t}{G_a(\omega_c)} = \frac{\pi}{4k^2 N \zeta} \quad (15)$$

$G_a(\omega_c)$ can be measured as the real part of the acoustic input admittance $Y_i(\omega_c)$, and ζ is a factor which takes into account the ratio of normalized center frequency conductances for different electrode structures as described previously. Solving for k^2 yields an effective value for the electro-acoustic coupling coefficient. As for the extracted value C_s^{eff} , the extracted value of k^2 takes into account the actual transducer structure as fabricated. Substituting k^2 and C_s^{eff} into equation (9) yields a value for ideal transducer center frequency conductance, G_o . Using the extracted values of G_o and C_t and equations (3) through (8) and (12), the real and imaginary parts of the input impedance and admittance

can be predicted and compared with experimental results to verify the extraction. The parameter extraction process was used in this capacity throughout the current work.

Accuracy of Parameter Extractions and Predicted Impedance Characteristics

Unweighted Transducers

Figure 16 shows a comparison between the measured input impedance of a 60 MHz unweighted split-finger transducer with aperture $W = 55 \lambda$ and $N = 5$ built on 112° lithium tantalate and the impedance predicted using parameter extraction and lumped equivalent circuit modeling. Agreement is quite good considering the simplicity of the techniques used. The room temperature values of the extracted material constants for this cut of LiTaO_3 are $k^2 = 0.009996$ and $C_s = 4.569$ pF/cm, reasonably close values published by Morgan, $k^2 = 0.0072$ and $C_s = 4.33$ pF/cm [55]. The standard deviation of the measurements of the extracted parameters was less than 2% of the mean value of the parameters, indicating relatively small measurement uncertainties.

Figure 17 shows a comparison between the measured input impedance of a 100 MHz unweighted split-finger transducer with aperture $W = 91 \lambda$ and $N = 5$ built on YZ lithium niobate and the impedance predicted using parameter extraction and lumped equivalent circuit modeling. Room temperature values of extracted material parameters obtained for YZ LiNbO_3 were $k^2 = 0.044$ and $C_s = 4.68$ pF/cm, quite close to the values published by Datta, $k^2 = 0.045$ and $C_s = 4.6$ pF/cm [53]. Once again, good agreement between theory and experiment is obtained.

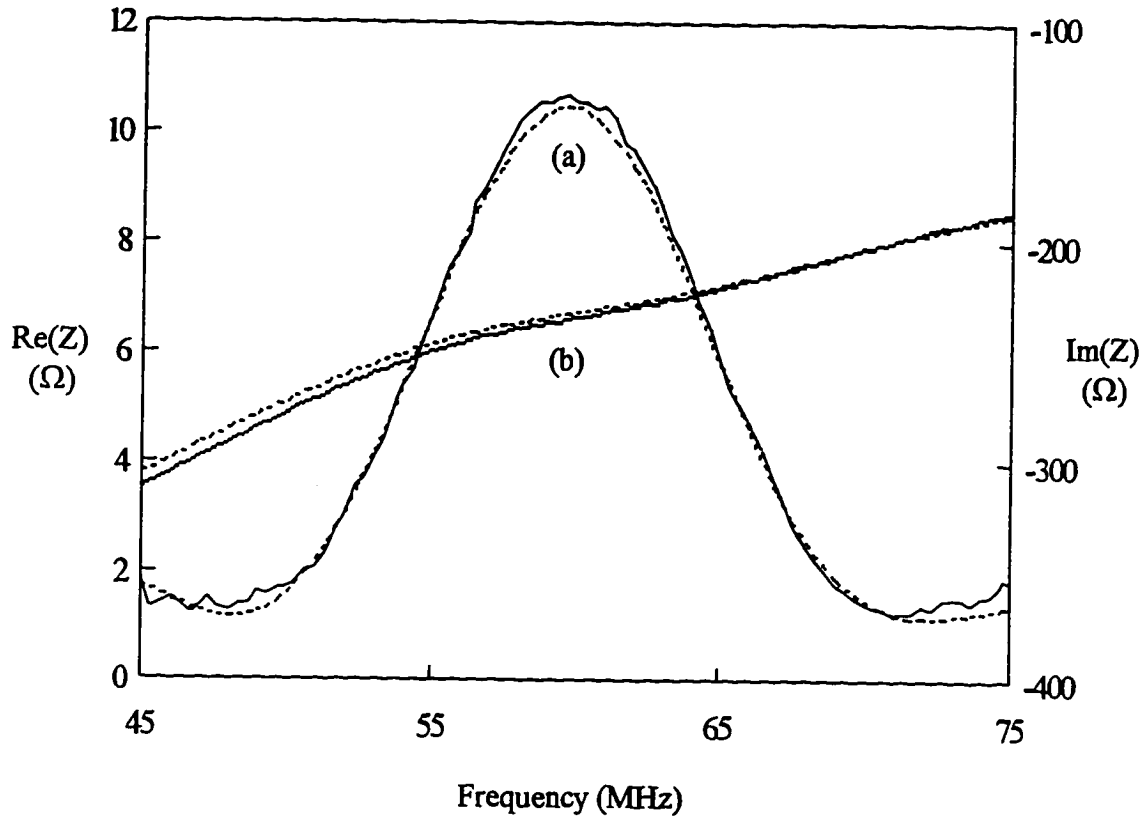


Figure 16. Comparison of modeled and measured impedance for LiTaO_3 device. Data presented is for a 60 MHz unweighted split-finger transducer with aperture $W = 55 \lambda$ and $N = 5$ built on 112° lithium tantalate. Solid line is experimental data, dotted line is calculated using lumped equivalent circuit model. (a) $\text{Re}(Z)$, (b) $\text{Im}(Z)$.

Apodized Transducers

The same equivalent circuit parameter extraction technique can be used to obtain center frequency values for apodized transducers, provided an effective number of transducer finger pairs N_{eff} is used in place of N . A 300 MHz device using apodized and

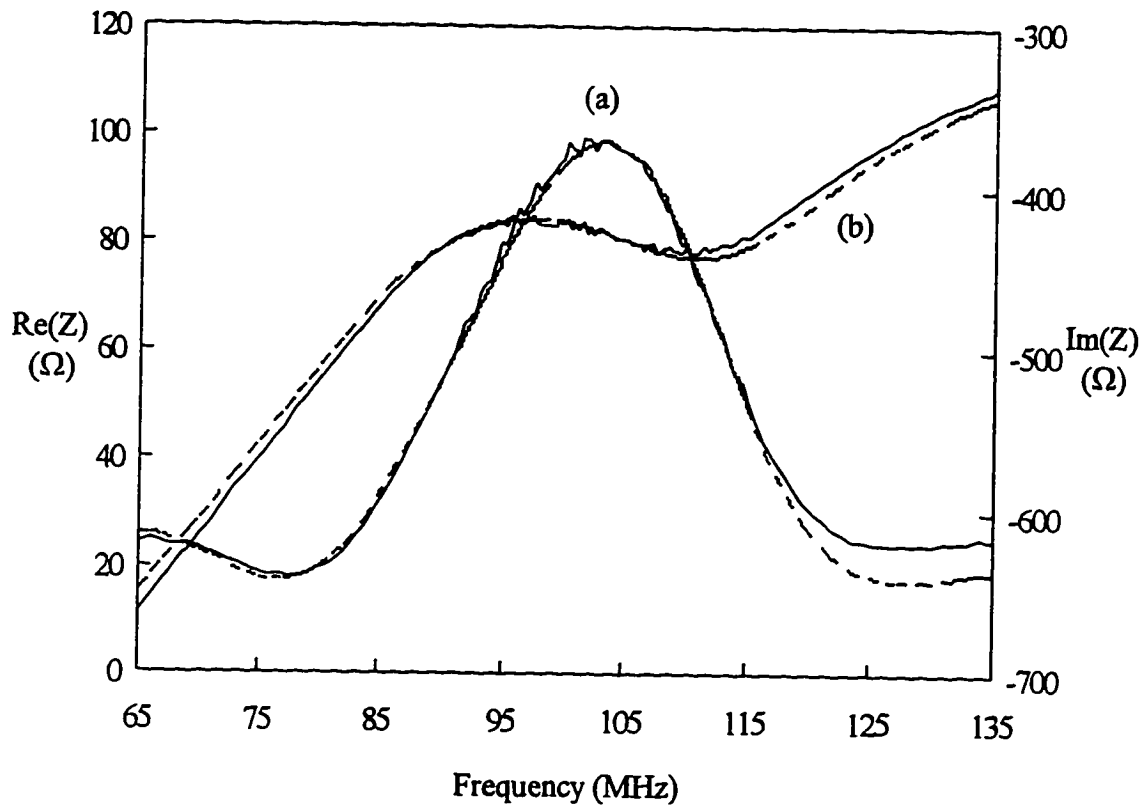


Figure 17. Comparison of modeled and measured impedance for LiNbO₃ device. Data presented is for a 100 MHz unweighted split-finger transducer with aperture $W = 91 \lambda$ and $N = 5$ built on YZ lithium niobate. Solid line is experimental data, dotted line is calculated using lumped equivalent circuit model. (a) $\text{Re}(Z)$, (b) $\text{Im}(Z)$.

withdrawal weighted transducers fabricated on ST quartz was analyzed using the present technique. Room temperature values of extracted material parameters obtained for ST quartz were $k^2 = 0.0011$ and $C_s = 0.522$ pF/cm, quite close to the values published by Datta, $k^2 = 0.0012$ and $C_s = 0.5$ pF/cm [53]. As shown in Figure 18, the predicted device

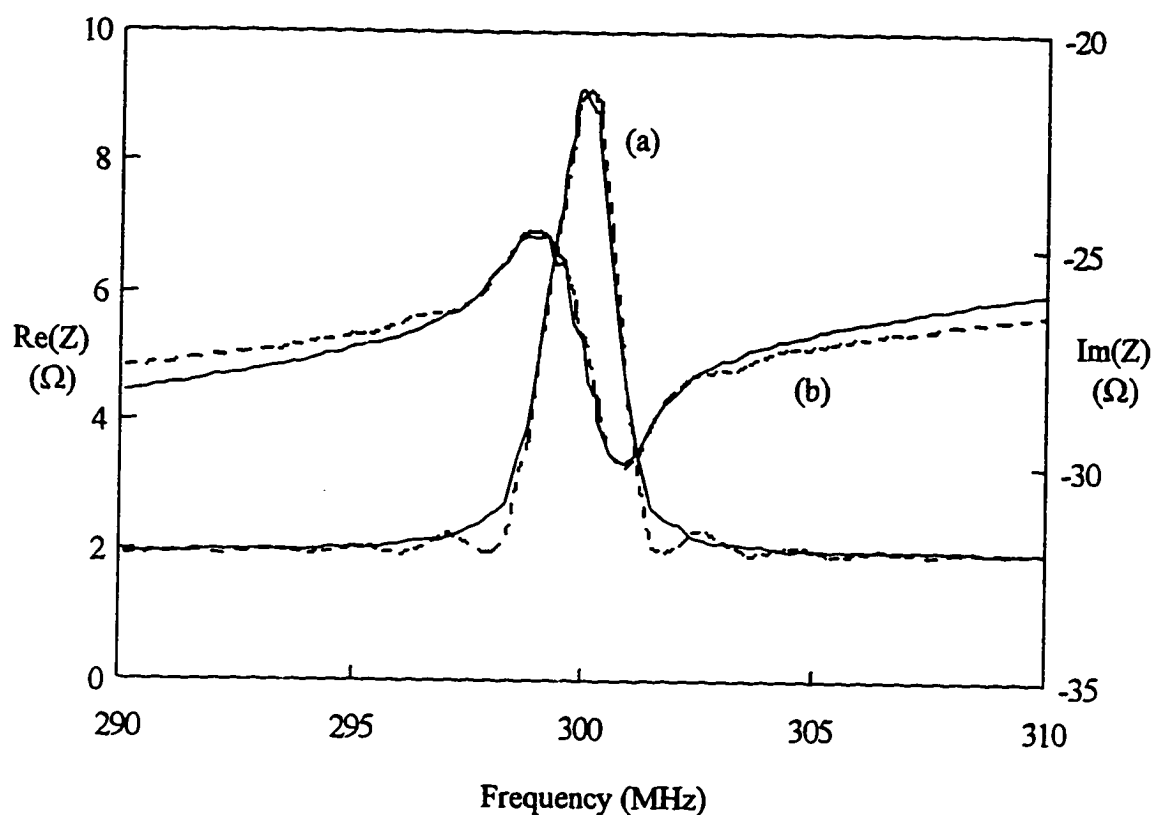


Figure 18. Comparison of modeled and measured impedance for ST quartz device. Data presented is for a 300 MHz apodized split-finger transducer built on ST quartz. Solid line is experimental data, dotted line is calculated using lumped equivalent circuit model. (a) $\text{Re}(Z)$, (b) $\text{Im}(Z)$.

impedance is in good agreement with experiment, and very good comparison with known parameters was obtained as described above.

Temperature Dependence of Extracted Parameters for LiTaO₃

A 60 MHz unweighted split-finger transducer with aperture $W = 55 \lambda$ and $N = 5$ built on 112° lithium tantalate was evaluated using the parameter extraction technique described above to determine the temperature dependence of the extracted parameters. Data was taken on this device over temperature from -50°C to $+85^\circ \text{C}$ in order to evaluate the temperature dependence of the material and circuit parameters extracted. Figures 19 through 21 illustrate the results of the circuit extraction over temperature for this device.

The values obtained for substrate capacitance and acoustic coupling coefficient for the lithium tantalate substrate used were found as the average of the extracted values for at least 5 devices. The raw data and best linear fits are shown in Figures 19 and 20.

The temperature coefficient of resistance (TCR) for the $1500 \text{ \AA}$ thick aluminum film was of interest because of its relationship to the device thin film loss. Of the loss mechanisms discussed previously, it is assumed that the only temperature dependent loss term will be the thin film loss (TFL) [9]. This is a reasonable assumption since none of the propagation or diffraction related losses vary with temperature, nor does the bi-directional or mismatch loss (assuming no change in matching components over temperature). As discussed in [9], the TFL is determined by the transducer series parasitic resistance R_t , and measurements of insertion loss variation over temperature can yield expressions for the TCR. In the current work, a simpler, direct parameter extraction approach was used. R_t was extracted for the device at each temperature, and the TCR was calculated using

$$TCR = \frac{R_t(T_2) - R_t(T_1)}{T_2 - T_1} \quad (16)$$

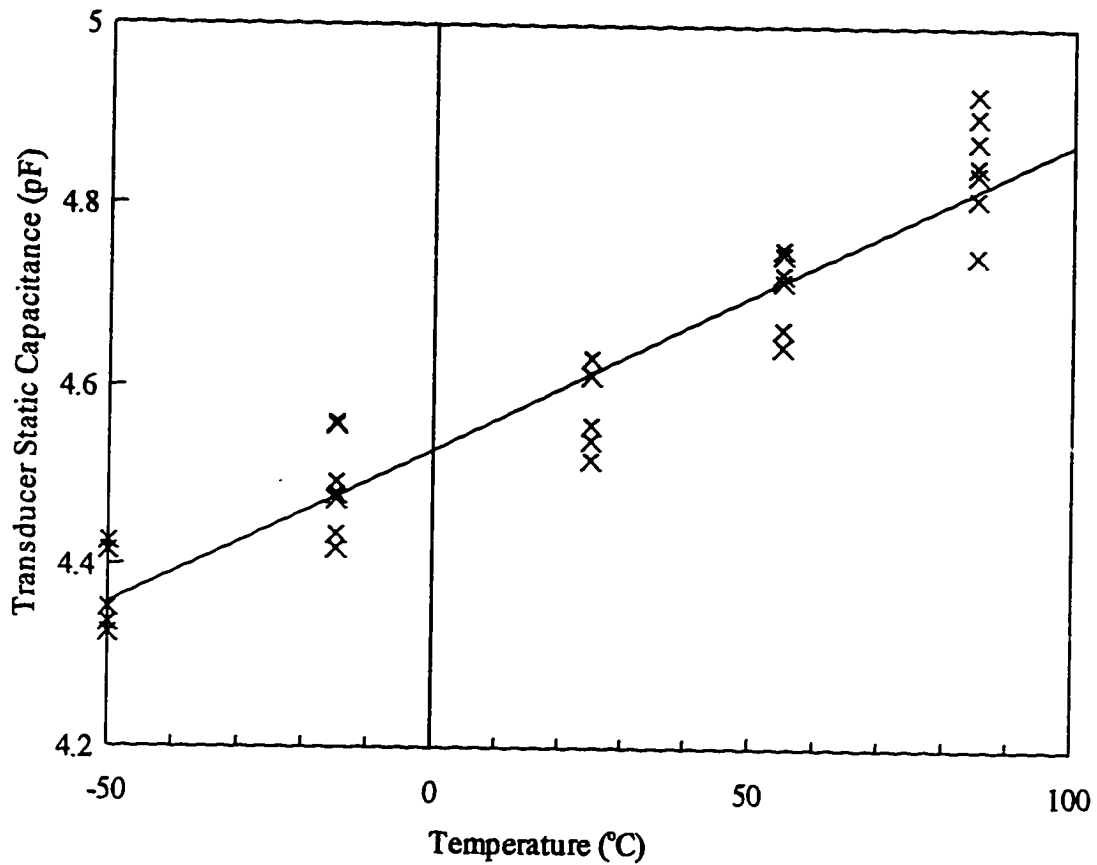


Figure 19. Temperature dependence of substrate effective dielectric constant C_s for 112° LiTaO_3 .

where T_1 and T_2 are the measurement temperatures in °C and R_t is measured in ohms.

This corresponds to the slope of the linear fit to R_t over temperature, shown in Figure 21.

Since the resistance of a thin metal film is directly proportional to the resistivity of the film, the temperature dependence of the resistance is identical to that of the resistivity.

The temperature coefficient of resistance for the 1500 Å thick aluminum film was found to be 0.00908 $\Omega/^\circ\text{C}$.

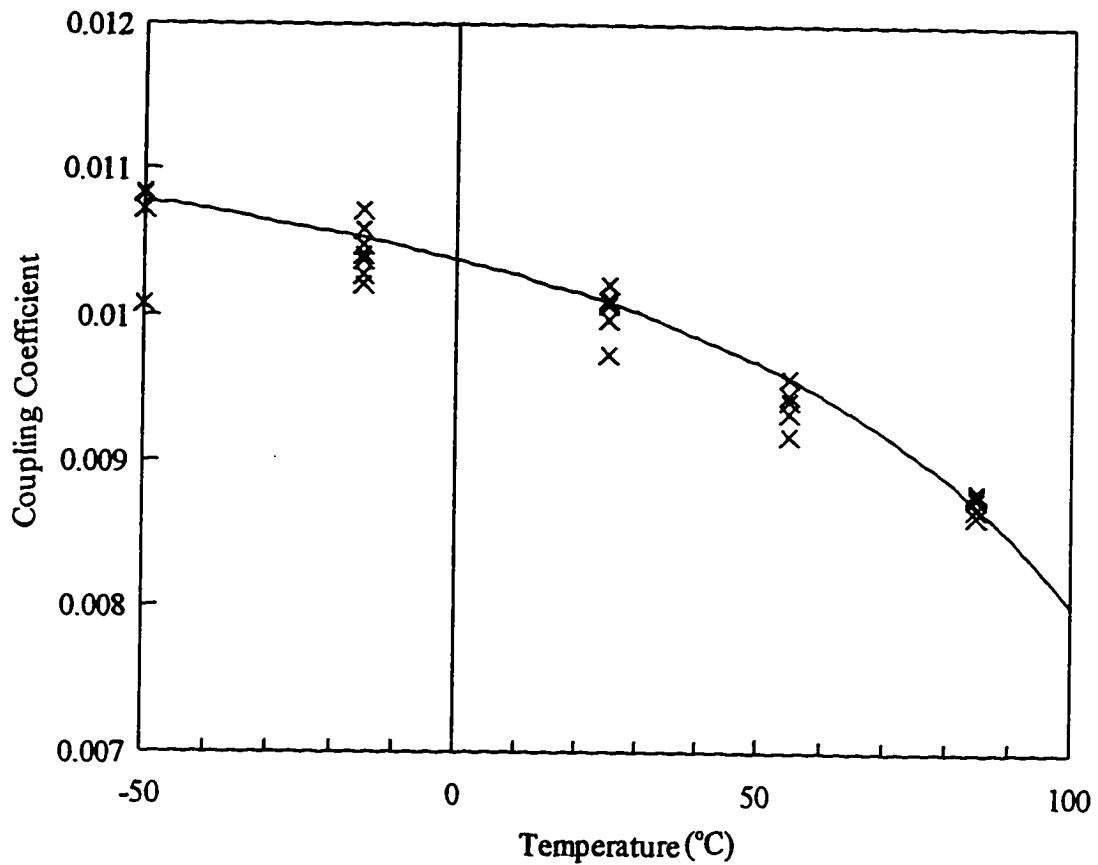


Figure 20. Temperature dependence of effective acousto-electric coupling coefficient k^2 for test devices on 112°LiTaO_3 .

Application To Unique Transducer Structures

The equivalent circuit parameter extraction technique presented above is particularly useful in model development for unconventional transducer structures, such as narrow gap or multilevel devices. In such cases, quantities such as transducer capacitance and effective coupling may not be easily calculated from previously known relationships. The parasitic thin film resistance can be found once again as the constant additive

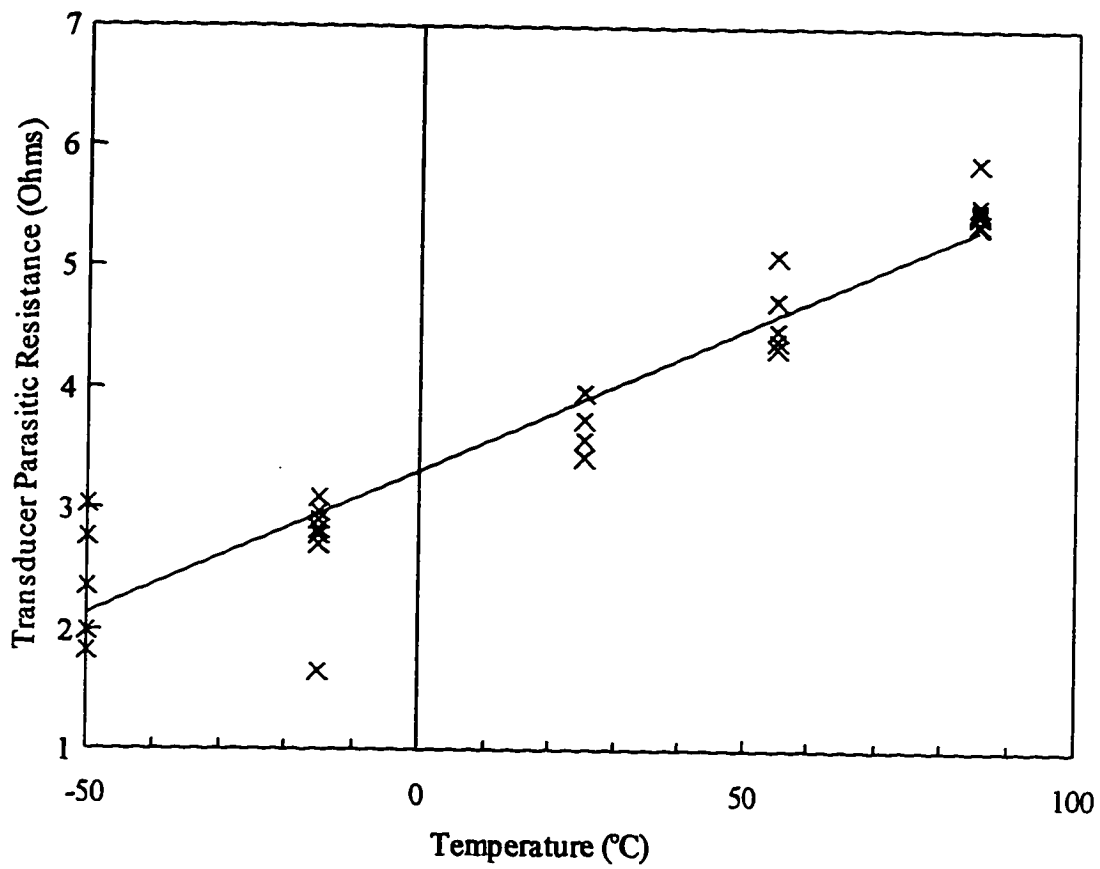


Figure 21. Temperature dependence of parasitic resistance for test devices on 112°
LiTaO₃.

component of the real part of the input impedance. Parameter extraction can then continue as described above, with extracted values of effective substrate dielectric constant used to calculate transducer capacitance, and the effective coupling coefficient calculated from measured values of Q_i . These values can then be used in either the lumped equivalent circuit model presented here or the transmission line model described in Chapter 6 to calculate predicted device performance and compare with experiment.

CHAPTER 4

SAW CHARACTERIZATION OF PECVD Si_3N_4 on LiNbO_3

Introduction

Various experimental test devices were utilized for Si_3N_4 film characterization. These devices consisted of unweighted transducers with three different center frequencies and nitride film test structures. Several configurations for the nitride layers were utilized, including pads covering a known portion of the propagation path and groups of reflective strips. Wafers were fabricated with several different nitride thicknesses, ranging from approximately 300 Å to 3600 Å.

SAW Device Design and Measurement

Simple delay lines were fabricated on 128° YX and YZ LiNbO_3 for measurement of the SAW properties, along with several test structures used solely for characterization of the nitride films. Three preliminary devices were designed having transducer wavelengths of 24 μm , 40 μm , and 80 μm . This corresponds to fundamental center frequencies of approximately 145 MHz, 87 MHz, and 44 MHz, respectively, assuming YZ LiNbO_3 substrates with SAW velocity equal to the nominal free surface velocity of 3488 m/sec. On 128° LiNbO_3 , with a free surface velocity of 3158 m/sec, this corresponds to

device center frequencies of 131 MHz, 79 MHz, and 39 MHz. Due to the variation in the actual SAW velocity caused by metal and film structures on the crystal surface, the actual device center frequencies varied substantially from these nominal values. All devices used for film characterization used split electrodes to eliminate internal transducer reflections. The transducers were 10λ long with seven dummy electrodes at each end and acoustic beam widths of 50λ . The devices generated both fundamental and odd harmonic responses, and measurements were made at the fundamental and all harmonic frequencies where RF feedthrough was suppressed relative to the SAW delay line response or could be gated out. This approach provided multiple data points of normalized Si_3N_4 film thickness without the need for design and fabrication of an excessively large number of wafers. Control devices were fabricated without the presence of silicon nitride thin films. Two port S-parameter data was obtained from the control devices at the fundamental and harmonic frequencies of interest. Through parameter extraction techniques discussed in Chapter 3, the transducer electrode thin film loss, electrical mismatch loss, and propagation loss were found at every frequency of interest. This technique of parameter extraction takes into account the effects of varying electrode duty cycle and small fabrication defects which affect thin film loss and electrical mismatch loss as a function of frequency [56].

Test devices were fabricated with silicon nitride film pads of varying thicknesses in the propagation path between the two transducers described above. The effect of the silicon nitride film on the SAW velocity was initially unknown, so the devices were designed such that the film region extended well beyond the edges of the SAW aperture to

eliminate possible waveguiding effects. The effective propagation length of the SAW under the silicon nitride film was approximately 10 mm and the transverse ends of the film were slanted to eliminate acoustic reflection effects. Device measurements were made at each frequency of interest. Parameter extraction was then conducted to eliminate the thin film and electrical mismatch losses for each transducer. The propagation loss from the control devices was then subtracted, leaving only the propagation loss due to the silicon nitride film. Velocity measurements were made by measuring the group delay of the S_{21} data at the frequencies of interest. The velocity data was corrected for free surface regions and for the regions under the transducer.

Propagation Loss Calculation

Typical bidirectional SAW devices have insertion losses of over 15 dB. This total insertion loss arises from several sources, the four main sources being bidirectional loss, mismatch loss, thin film loss, and diffraction loss. Each of these sources of loss will be considered separately.

Bi-directional Loss

Standard SAW devices utilize transducers which launch acoustic energy in two directions on the crystal surface, known as bi-directional transducers. Since half of the energy is launched in each direction, a loss of $10 \log(0.5)$, or approximately 3 dB, is incurred when the wave is launched onto the surface by the input transducer. Likewise, since SAW transducers are reciprocal devices, only half of the energy incident on an

acoustic port of a bi-directional SAW transducer will be converted into an electrical signal under conjugately matched conditions. The remaining half of the signal is re-radiated back toward the input transducer and leads to what is referred to as the triple transit signal. Thus an additional 3 dB loss arises when the wave is received at the output transducer. Taken together, these lead to a 6 dB total increase in the device insertion loss due to bi-directionality. This loss is unavoidable when bi-directional transducers are used. Transducer structures which are unidirectional, and hence launch or receive acoustic energy in only one direction, however, have been developed in recent years. A number of these structures are discussed in the section on low loss techniques in Chapter 7. Such devices, while often requiring complex matching, can result in eliminating the bi-directional loss almost entirely, reducing the overall insertion loss by 6 dB.

Mismatch Loss

Typical SAW devices have input impedances which differ substantially from the impedance of the system in which they are tested or used. Most network analyzers, for instance, present 50 Ω impedances to the device under test, while a SAW device can easily have a capacitive input impedance with magnitude of several hundred ohms. This mismatching between the electrical characteristics of the SAW device and the surrounding system leads to inefficiencies in the conversion of power from electrical to acoustic power and vice versa. Mismatch loss (MML) is defined as [9]

$$MML \equiv \frac{\text{Power Available From Load} - \text{Power Reflected From Port}}{\text{Power Available From Load}} \quad (17)$$

or the ratio of the power transmitted to the port and the power available from the load.

The reflection coefficient Γ is the linear magnitude of the reflection scattering parameter S_{11} (or S_{22}) which can be measured on a network analyzer. Since S_{11} is an amplitude reflection coefficient, it must be squared in the calculation of reflected power

$$\text{Power Reflected From Port} = |S_{11}|^2 (\text{Power Available From Load}) . \quad (18)$$

Thus, mismatch loss can be calculated as

$$MML = -10 \log(1 - |S_{11}|^2) . \quad (19)$$

Thin Film Loss

Thin metal films such as the aluminum used for fabrication of the electrode fingers on SAW devices generally have a finite resistance. The thinner the film, the higher this resistance tends to be. Thin film resistance leads to ohmic losses due to power dissipated in the resistance of the electrodes and bond pads of a SAW device. This loss can be reduced by using thicker metal films where possible, and the effects of this loss can be included in the SAW equivalent circuit model as a parasitic resistance term or terms. The transducer parasitic resistance can be extracted using the transducer bulk equivalent circuit model parameter extraction technique presented in Chapter 3. The thin film loss can be calculated using the value of the transducer parasitic resistance extracted from measured data as [9, 34, 57]

$$\text{Thin Film Loss} = \frac{P_a}{P_t} = \frac{P_a}{P_a + P_p} \equiv TFL \quad (20)$$

where P_a is the acoustic power radiated by the transducer and P_p is the power dissipated by the parasitic resistance so that P_t represents the total power absorbed by the transducer from the source. These values are given by

$$P_p = |i_{in}|^2 R_t \quad (21)$$

$$P_a = |i_{in}|^2 R_a \quad (22)$$

and

$$P_t = |i_{in}|^2 (R_t + R_a) \quad (23)$$

So we can write, in dB

$$TFL = 10 \log \left(1 + \frac{R_a}{R_t} \right) \quad (24)$$

where the expression given in equation (3) is used to calculate the radiation resistance R_a , and the extracted value of the transducer parasitic resistance R_t is used.

Diffraction Loss

Diffraction is the spreading of the surface wave wavefront on the crystal surface, and is an effect that occurs to some extent in all devices. Diffraction can lead to distortion of the ideal device frequency response, and increased insertion loss due to acoustic energy not being intercepted by the output transducer. For devices with transducer apertures which are large compared to the acoustic wavelength at device center frequency and which have propagation paths which are not very long in acoustic wavelengths, the effects of diffraction on device performance are generally small. Such devices are said to be

operating in the near field, using a term borrowed from optics. Extremely long and narrow devices, or very high frequency devices, can be operating in the far field, leading to significant increases in insertion loss due to the effects of diffraction. Diffraction effects can be reduced by using a substrate such as YZ LiNbO₃, which has anisotropic velocity characteristics which tend to make it self-collimating. Diffraction loss (DL) can be estimated using a universal diffraction loss curve as given by [58], and included in the calculation of overall device insertion loss.

Propagation Loss

Additional losses are caused by the viscous forces between neighboring particles within the SAW crystal substrate creating a damping effect on the wave. These losses generally depend on the substrate material and are referred to as propagation loss. Losses due to air loading of the crystal surface and beam steering are also included in the propagation loss. Propagation loss (PL) can be isolated by subtracting the loss due to other mechanisms from the measured device insertion loss (IL),

$$PL = IL - TFL_1 - TFL_2 - MML_1 - MML_2 - BDL \quad (25)$$

where TFL_1 and TFL_2 represent the thin film losses of transducers 1 and 2, MML_1 and MML_2 represent the mismatch losses of ports 1 and 2, BDL represents the bi-directional loss, and DL represents the diffraction loss.

Propagation loss was calculated for control devices without silicon nitride film overlays, and was also calculated for devices with silicon nitride pads in the propagation

path to determine the effect of these films on propagation loss. Figure 22 shows the linear characteristic of measured SAW propagation loss versus normalized film thickness for Si_3N_4 films on both YZ LiNbO_3 and 128° LiNbO_3 . The PECVD films selected for use in acoustic devices show propagation loss much lower than the 0.02 dB/ λ reported for SiO_2 sputtered films of equivalent normalized thickness on LiNbO_3 [9, 33, 34]. It is believed that the low propagation loss observed is a result of high quality films with few voids.

SAW Velocity Calculation

The test structures used to calculate SAW velocity consisted of pairs of identical delay lines, one with a known region of the SAW propagation path coated with Si_3N_4 and the other with no film. Because the SAW velocity varies in different regions of the device, in order to obtain accurate velocity values it was necessary to carefully correct the velocity data for the different regions. The process used for this calculation is described below.

Device group delay was measured at center frequency of the fundamental and harmonic responses. An overall effective device velocity was then calculated from the known transducer separation and the measured device delay

$$v_{eff} = \frac{\text{separation}}{\tau} . \quad (26)$$

Since the transducer has a known wavelength which is set by the photomask geometry, and the velocity under the transducer combined with the wavelength determine the device center frequency, the velocity in the transducer region can be calculated by

$$v_{trans} = \lambda f_o . \quad (27)$$

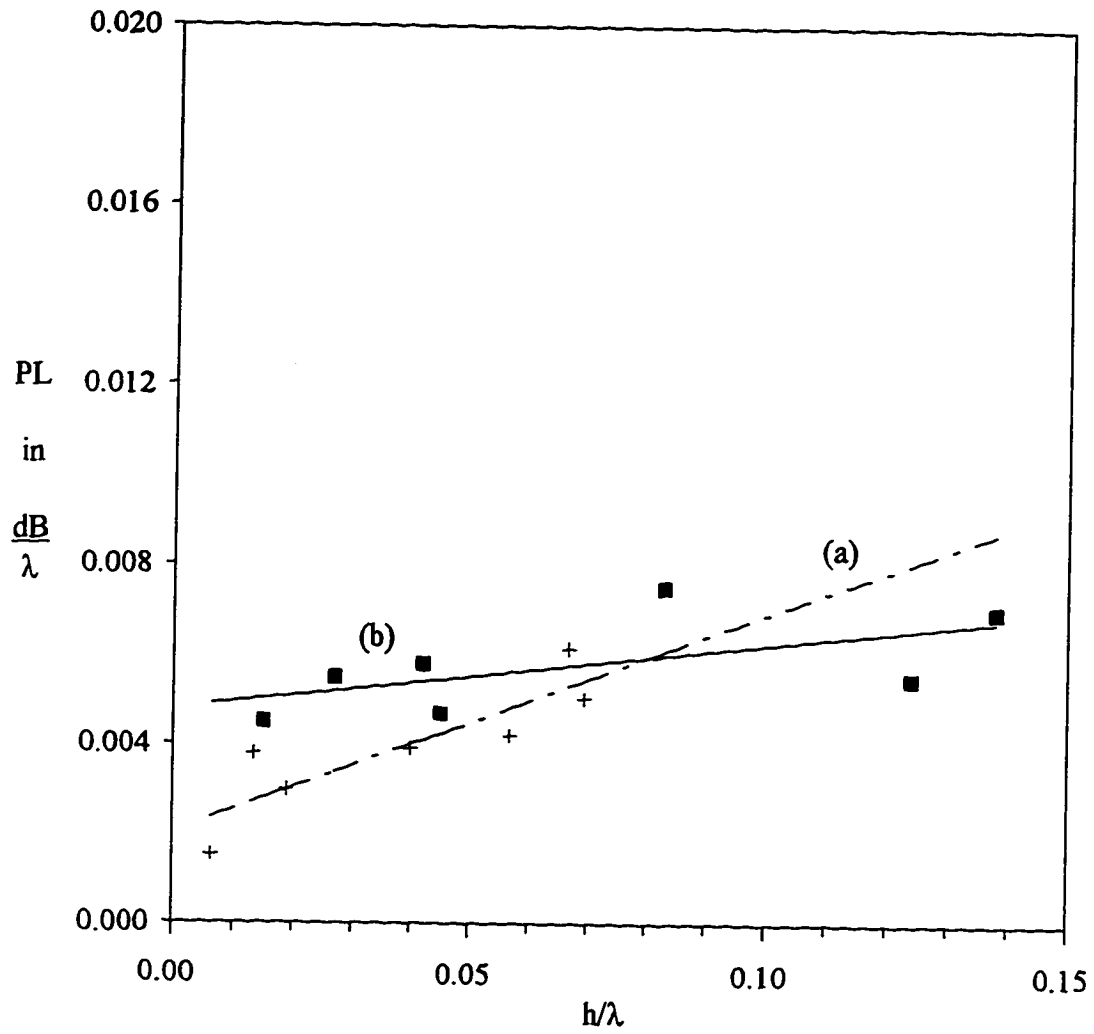


Figure 22. SAW propagation loss due to Si_3N_4 film overlays in dB/ λ vs. normalized film thickness. Film thickness is h , acoustic wavelength is λ . (a) Films deposited on YZ LiNbO_3 , (b) Films deposited on 128° LiNbO_3

Because the precise transducer length is also known, this velocity can be used to find the portion of the overall device delay associated with propagation of the wave underneath the transducer regions. This is given by

$$\tau_{trans} = \frac{\text{transducer length}}{v_{trans}} \quad (28)$$

The portion of the overall device delay attributable to wave propagation in the free surface regions or for the regions under the nitride film can be found by subtracting the transducer delay from the overall measured device delay,

$$\tau_{region} = \tau - \tau_{trans} \quad (29)$$

The velocity in this region can then be found from the known length of the region and the measured region delay,

$$v_{region} = \frac{\text{length}}{\tau_{region}} \quad (30)$$

This calculation was performed for control devices without silicon nitride films to verify the validity of the procedure by confirming the known free surface velocity of the YZ LiNbO₃ substrates. A free surface velocity of 3488.9 m/sec was obtained, with a standard deviation of 0.27%, in line with published values for this material [53, 59].

The SAW velocity under silicon nitride films was calculated in the same manner. The SAW velocity under the PECVD Si₃N₄ films calculated from measured data for films deposited on 128° YX and YZ LiNbO₃ is shown versus normalized film thickness in Figure 23. For both substrate cuts, the SAW velocity is faster under a silicon nitride film

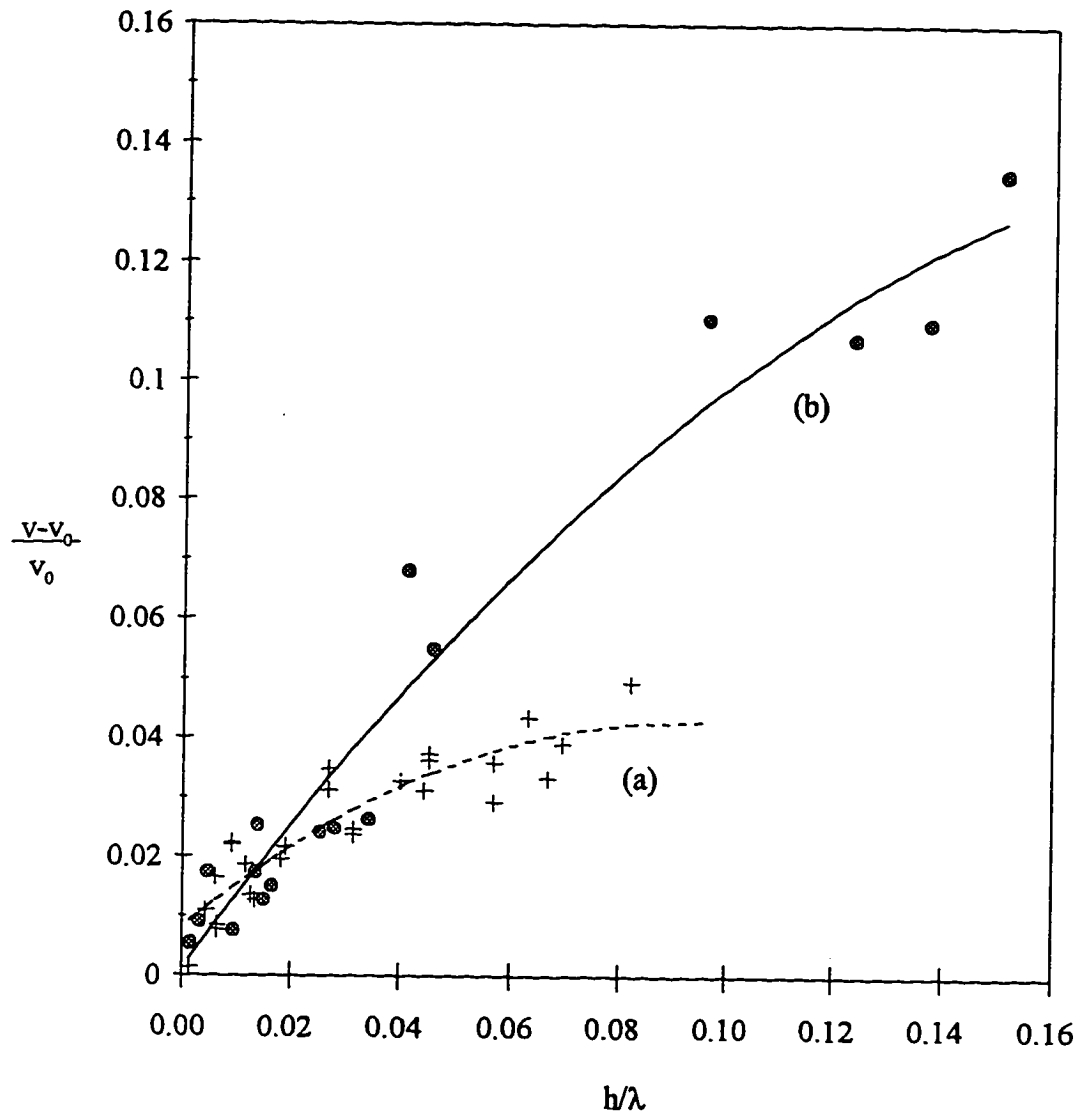


Figure 23. SAW velocity dispersion vs. normalized Si_3N_4 film thickness on LiNbO_3 . Film thickness is h , acoustic wavelength is λ . (a) Films deposited on YZ LiNbO_3 , (b) Films deposited on 128° LiNbO_3

than on a free surface, indicating that the film is stiffening the surface. As film thickness increases, the rate of increase of velocity with increasing film thickness decreases, implying that the film becomes less dense as it grows [39]. This decrease in film density with increasing film thickness was not observed in the measured film density values, perhaps due to measurement uncertainty. The difference in velocity dispersion observed for the two crystal cuts may correspond to the difference in the compressional and shear elastic constants, c_{11} and c_{44} . The compressional elastic constant c_{11} is directly related to the SAW velocity, and is the factor most influenced by the application of a stiffening film such as silicon nitride. Thus the larger velocity dispersion observed for 128° YX LiNbO₃ may be due to the stiffening effect on the larger c_{11} of this cut.

Reflectivity

Reflection Mechanisms

Reflections of surface acoustic waves propagating in piezoelectric crystal substrates arise from two categories of phenomena, mechanical and electrical. The two basic mechanical reflection mechanisms are referred to as mass loading and geometric discontinuities. Mass loading is an effect brought about by the difference in density and elastic properties between an overlaying stripe and the substrate material [60]. In instances such as grooved surfaces, where the stripes consist of the same material as the substrate, the mechanical reflections are caused by geometric discontinuities. A geometric

or topographic change in the surface on which the SAW is propagating can lead to a reflection [60].

The basic electrical mechanisms leading to reflections are piezoelectric shorting and electrical regeneration. On substrates with high electro-acoustic coupling (k^2), conductive layers which short out the electric field at the surface of the device lead to substantial reflections. Additionally, when conductive strips which are not shorted together are on the surface of a piezoelectric through which a surface wave travels, the electric field accompanying the mechanical surface wave will induce a potential difference between separate strips. This electric potential will then regenerate an acoustic wave in a process known as regeneration [60]. Both of these effects lead to reflections.

Mechanical reflection mechanisms occur in both highly coupling substrates such as LiNbO_3 and weakly coupling substrates such as quartz. Electrical reflection mechanisms, while present on both substrates, are so weak on substrates such as quartz that in many cases they can be neglected. On LiNbO_3 , however, electrical reflection mechanisms are often dominant.

A number of interesting types of SAW devices can be built which utilize the reflective properties of various structures. Silicon nitride films have the potential for use in such reflective structures, if they provide sufficient levels of reflectivity. As nonconductive films, the mechanisms which cause reflections should be principally mechanical. Simple reflection theory based on dimensional arguments alone [61] states that the reflection coefficient is a function of the normalized thickness of a film,

$$r\left\{\left(\frac{h}{\lambda}\right)\right\} = r_o + C\left(\frac{h}{\lambda}\right) + \text{higher order terms} . \quad (31)$$

For conducting films, as the thickness of the film goes to zero, the constant r_o represents the finite reflection coefficient due to the electrical shorting effect of the film. For a nonconductive layer, however, r_o should be zero, implying that there will be no reflectivity as the film thickness goes to zero for such films.

Reflectivity Calculation

Simple delay line devices at approximately 145 MHz center frequency were fabricated on YZ LiNbO₃ with a reflector composed of 100 silicon nitride strips of width $\lambda/4$ between the transducers in order to calculate strip reflectivity. The transmission between transducers is shown in Figure 24 for a device with a Si₃N₄ film 2350 Å thick. The notch does not occur at the transducer center frequency due to the higher velocity of the SAW under the silicon nitride surface as compared to the SAW transducer velocity. The magnitude of the notch at the frequency of maximum reflectivity of the grating relative to the non-reflecting level gives the transmission coefficient of the grating, T [60, 62]. The relationship

$$T = \frac{2R^N}{R^{2N} + 1} \quad (32)$$

gives the transmission coefficient in terms of R, a reflection coefficient characteristic of the strips, and N, the number of reflector strips. R can be written in terms of the reflectivity per stripe, r, as

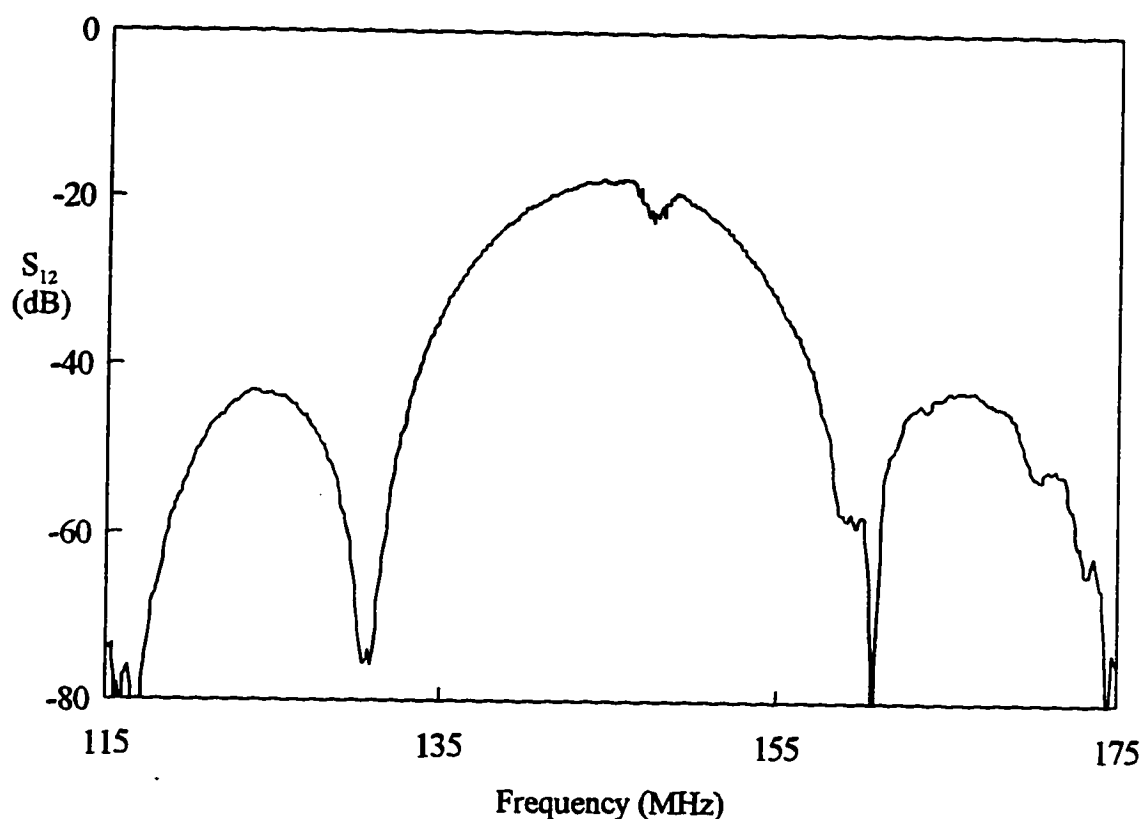


Figure 24. Transmission data for a 100 strip Si_3N_4 reflector of thickness 2350 Å between two unweighted 145 MHz transducers on YZ LiNbO_3 .

$$R = \frac{1 + \frac{r}{2}}{1 - \frac{r}{2}} \quad (33)$$

Measuring the notch depth and calculating the strip reflectivity yielded the data shown in Figure 25. Assuming a linear variation with respect to normalized film thickness (h/λ) as predicted by conventional theory [61, 63], the reflectivity per strip is calculated using linear regression as $0.7411(h/\lambda) + 0.0023$ for film thicknesses between $0.006(h/\lambda)$ and $0.016(h/\lambda)$. For a perfectly nonconductive strip, it at first seems odd that the reflectivity

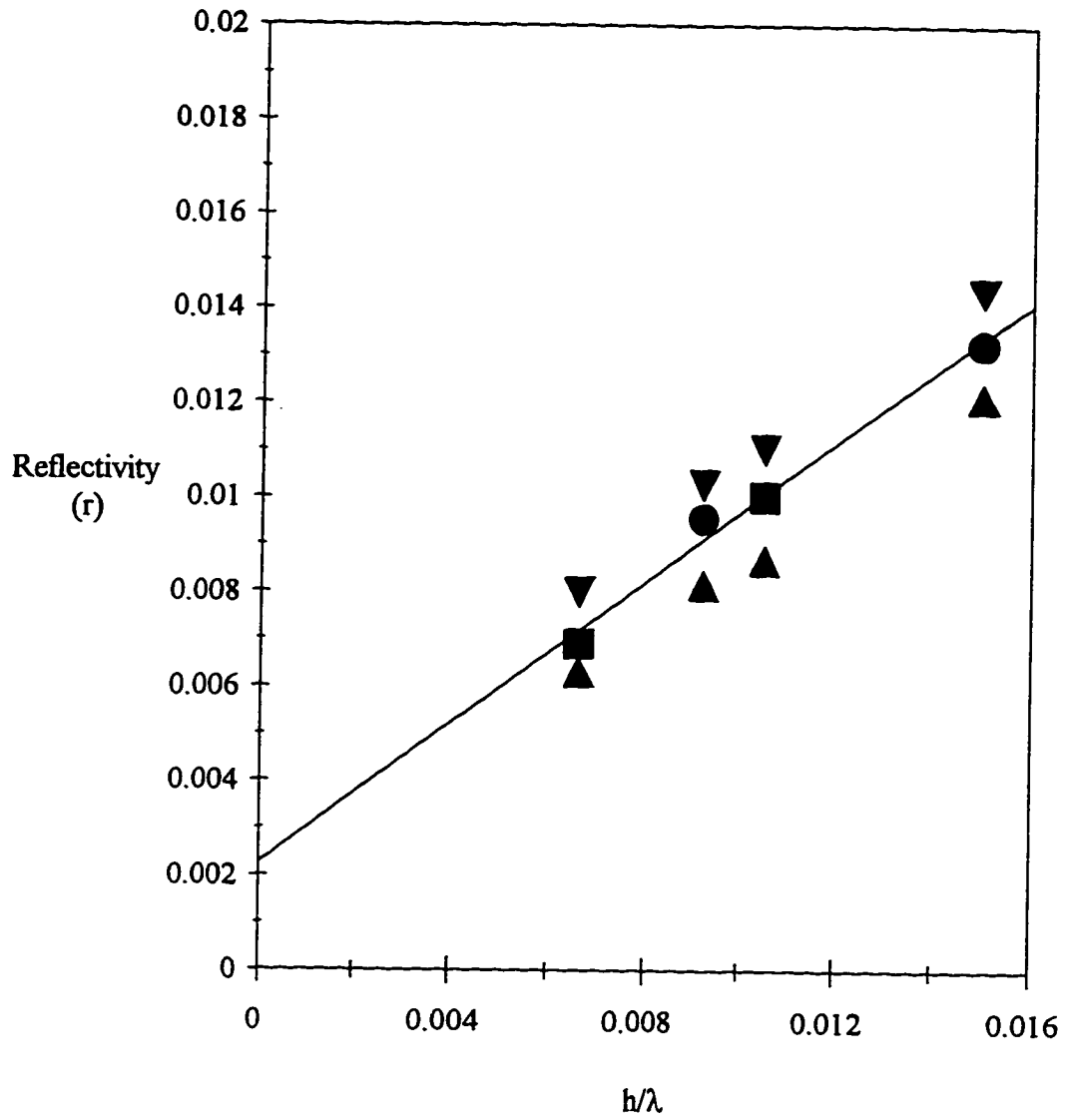


Figure 25. Reflectivity per strip for Si_3N_4 on YZ LiNbO_3 . Upper and lower triangles represent maximum and minimum, squares represent average values for measured reflectivity per strip. Film thickness is h , acoustic wavelength is λ .

does not equal zero when the strip thickness goes to zero. Certainly the mass loading and geometric discontinuity effects would disappear at that thickness. However, the effects which cause reflection from a nonconductive strip include not only mass loading, but some second order electric field effects as well. Placing a substance such as silicon nitride, with a dielectric constant different from the crystal substrate, on the surface of the device will lead to slight variations in the electrical environment of the wave. Robinson and Hahn have discussed the fact that dielectric properties of a nonconductive film overlay on a SAW device can cause slight electrical effects [64]. Such effects could lead to the small non-zero reflectivity extrapolated for devices with silicon nitride films of zero thickness.

The measured reflectivity is higher than grooves on YZ LiNbO₃, which have a reflectivity of approximately $0.67(h/\lambda)$ [58]. Shorted and unconnected thin aluminum lines on YZ LiNbO₃ reportedly have reflectivities of approximately 0.018 and 0.011, respectively [60]. These values are essentially independent of metal thickness, since piezoelectric shorting and electrical regeneration effects (for the unconnected lines) are the dominant reflection mechanisms on high coupling substrates such as LiNbO₃, rather than mass loading or geometric discontinuities. It can be seen from the expressions above that reflectivities equal to or larger than those for metallic strips can be achieved on LiNbO₃ using moderate thicknesses of PECVD silicon nitride films. For example, a nitride film with thickness of less than $2\%(\lambda)$ on YZ LiNbO₃ would result in a reflectivity equal to that of shorted metal strips. It is evident that such films can be used to provide reflective structures useful in a wide range of acoustic devices.

Summary

High quality silicon nitride films suitable for SAW applications were deposited by a PECVD process using silane-ammonia as the reactant gas mixture. These films have low acoustic attenuation and relatively high reflectivity, and could be used for passivation, frequency tuning, dielectric reflectors, waveguides, and other applications requiring a low loss dielectric film.

CHAPTER 5

EXPERIMENTAL RESULTS, EQUIVALENT PARAMETER EXTRACTION, AND ANALYSIS OF MULTILEVEL DEVICES

Introduction

An array of experimental test structures fabricated on YZ LiNbO₃ were utilized in the current work. These structures included 100 MHz and 500 MHz devices utilizing the multilevel transducer configurations presented in Chapter 1, as well as conventional single-level split finger 50 MHz control devices and test structures used for nitride film characterization. Transducers with nominal apertures of 10λ and 50λ were tested. The electrode linewidths for the 100 MHz multilevel devices were $17.44\ \mu\text{m}$, while the linewidths for the 500 MHz devices were $3.488\ \mu\text{m}$. These values clearly demonstrate the potential benefit to developing this type of transducer structure, since a split finger transducer with fundamental operating frequency of 500 MHz on YZ lithium niobate would normally have a linewidth of less than $0.9\ \mu\text{m}$. Both unweighted and overlap apodized devices were fabricated at 500 MHz, with all 100 MHz devices being unweighted. Several configurations for the intermediate nitride layer were utilized, including pads covering the entire propagation path, pads covering just the local transducer area, groups of reflective strips, and others. Devices were fabricated with

interdigitated or solid upper electrodes. The types of 100 MHz and 500 MHz devices fabricated in these experiments are shown in Figures 26 and 27.

Wafers were fabricated with six different nitride thicknesses, ranging from 400 Å to approximately 3000 Å. The equivalent circuit parameter extraction technique presented in Chapter 3 was used to evaluate unknown equivalent circuit parameters for these transducer structures. Values of effective substrate dielectric constant extracted using the equivalent circuit parameter extraction technique presented in Chapter 3 were used to calculate transducer capacitance and to obtain effective coupling coefficient values. These values were then used in the lumped transducer equivalent circuit model to calculate predicted device impedance and admittance and to compare with experiment.

Comparison of Control and Multilevel Devices

The unmatched response of a typical 50 MHz unweighted split finger transducer device with electrodes 8.72 μm wide is shown in Figure 28. These devices were utilized as control devices for comparison purposes throughout this experiment. The unmatched response of a 100 MHz multilevel device with interleaved upper and lower electrode patterns is shown in Figure 29. The fractional bandwidth of the 100 MHz device is 40%, equal to that of the 50 MHz device. The electrodes on the multilevel device are 17.44 μm wide, and the device shown had an intermediate nitride layer 935 Å thick. Comparing the two responses, we note that both exhibit the $\sin(x)/x$ frequency response characteristic of a simple unweighted transducer, which has a rectangular time domain impulse response. The insertion loss of the multilevel device is 22.018 dB, lower than the 24.38 dB insertion

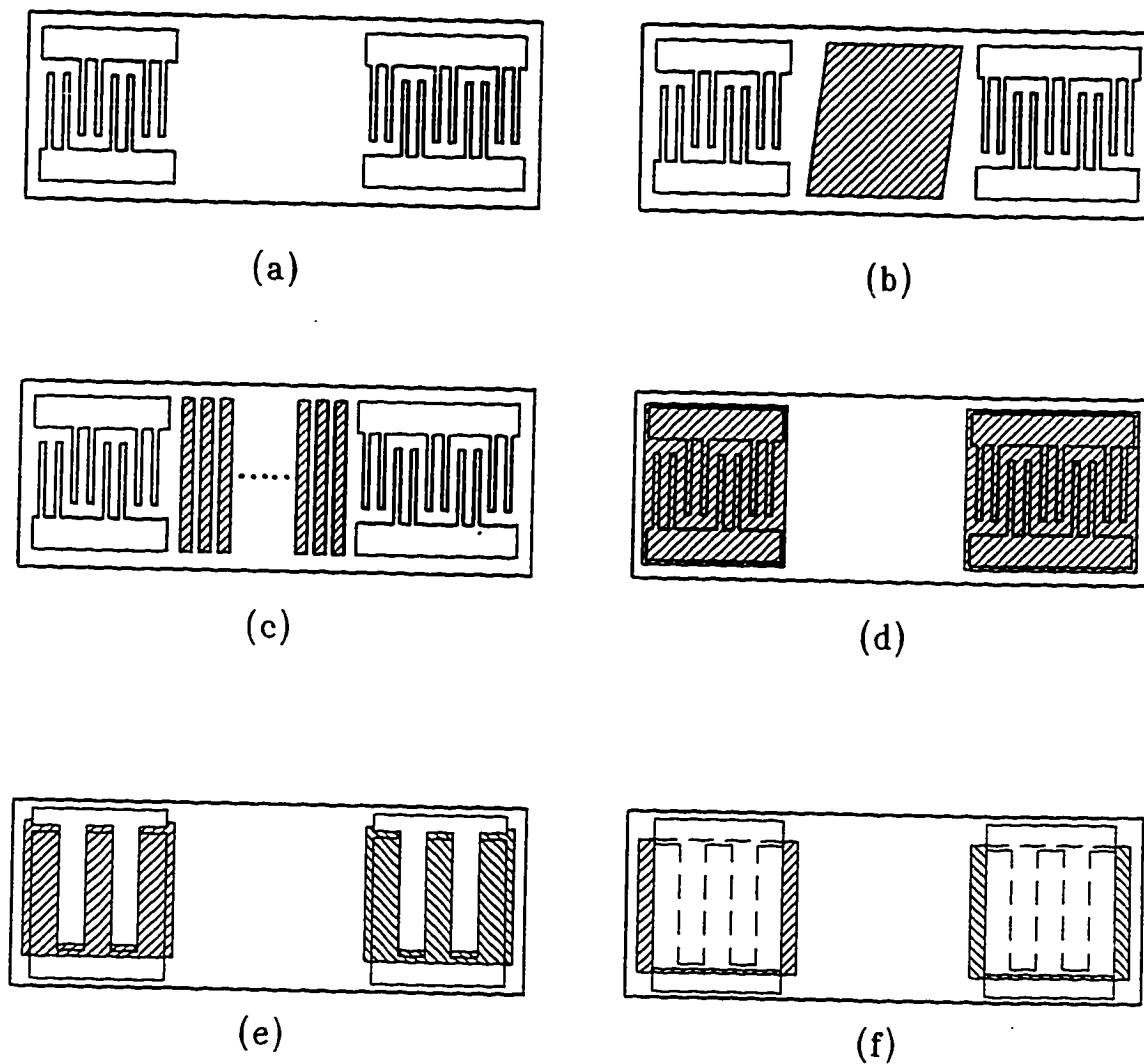


Figure 26. SAW test structures for 50 MHz control devices and 100 MHz multilevel devices. Single level split finger transducers used in (a) - (d), multilevel transducers in (e) and (f). (a) Control device, (b) Nitride pad in propagation path, (c) Nitride reflector strips, (d) Nitride over transducer, (e) Interdigitated upper electrode, (f) Solid upper electrode.

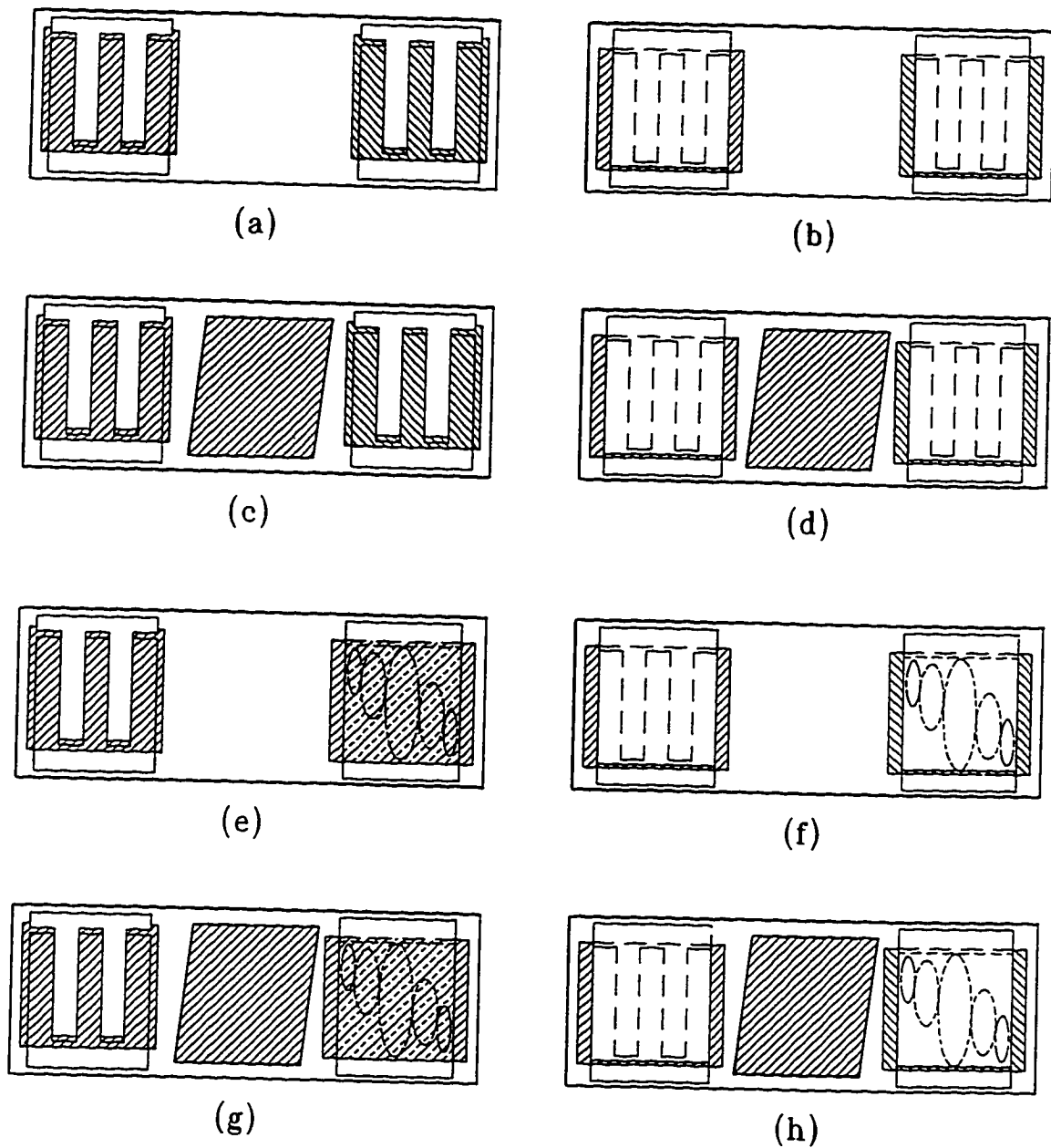


Figure 27. SAW test structures for 500 MHz multilevel devices. Multilevel transducers have interdigitated upper electrode in (a), (c), (e), and (g), and solid upper electrodes in (b), (d), (f), and (h). (a) and (b) Delay lines, (c) and (d) Nitride in propagation path, (e) and (f) Delay lines with one apodized transducer, (g) and (h) Delay lines with one apodized transducer and nitride in propagation path.

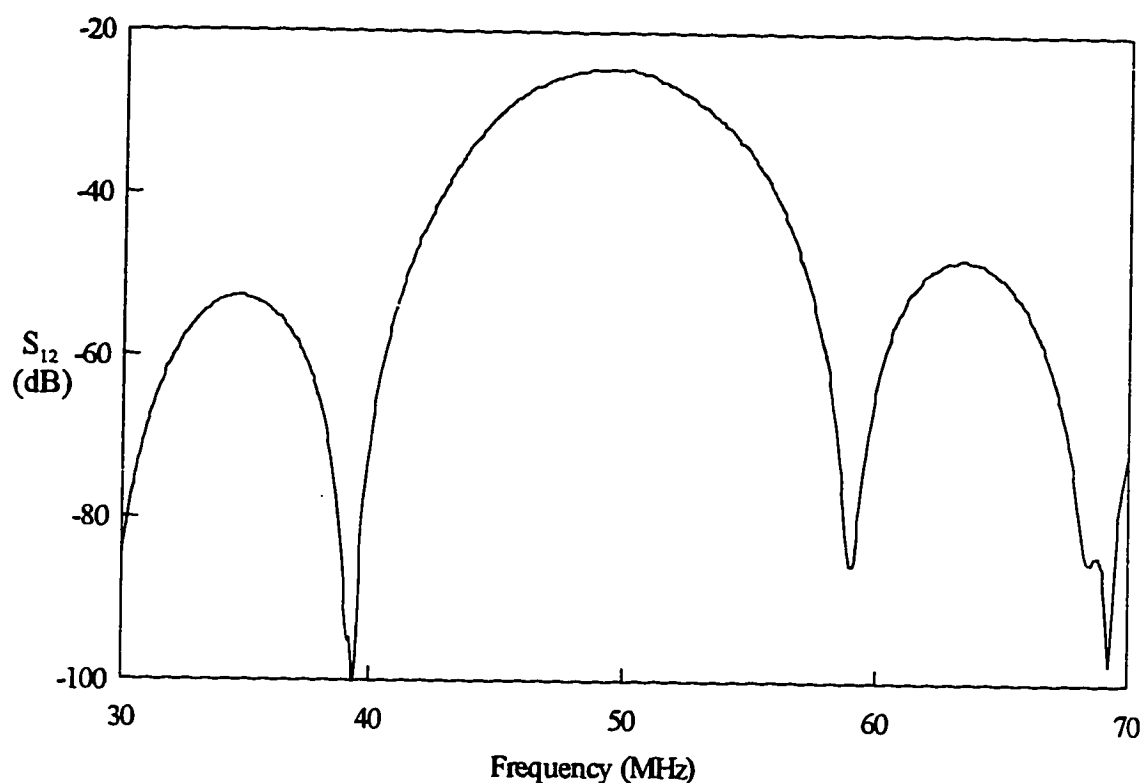


Figure 28. Control device frequency response. Unmatched response of a 50 MHz delay line using split-finger single level transducers on YZ LiNbO₃. Electrode width is 8.72 μm .

loss of the control device. Parameter extraction and calculation of the various components of insertion loss for each device showed that the lower loss is principally due to lower mismatch loss for the multilevel device. This demonstrates one desirable device characteristic made possible by controlling the transducer input impedance by varying the dielectric layer characteristics. As a result, devices fabricated which were similar to the 100 MHz device shown in Figure 29 exhibited insertion losses ranging from approximately 20 dB to approximately 35 dB.

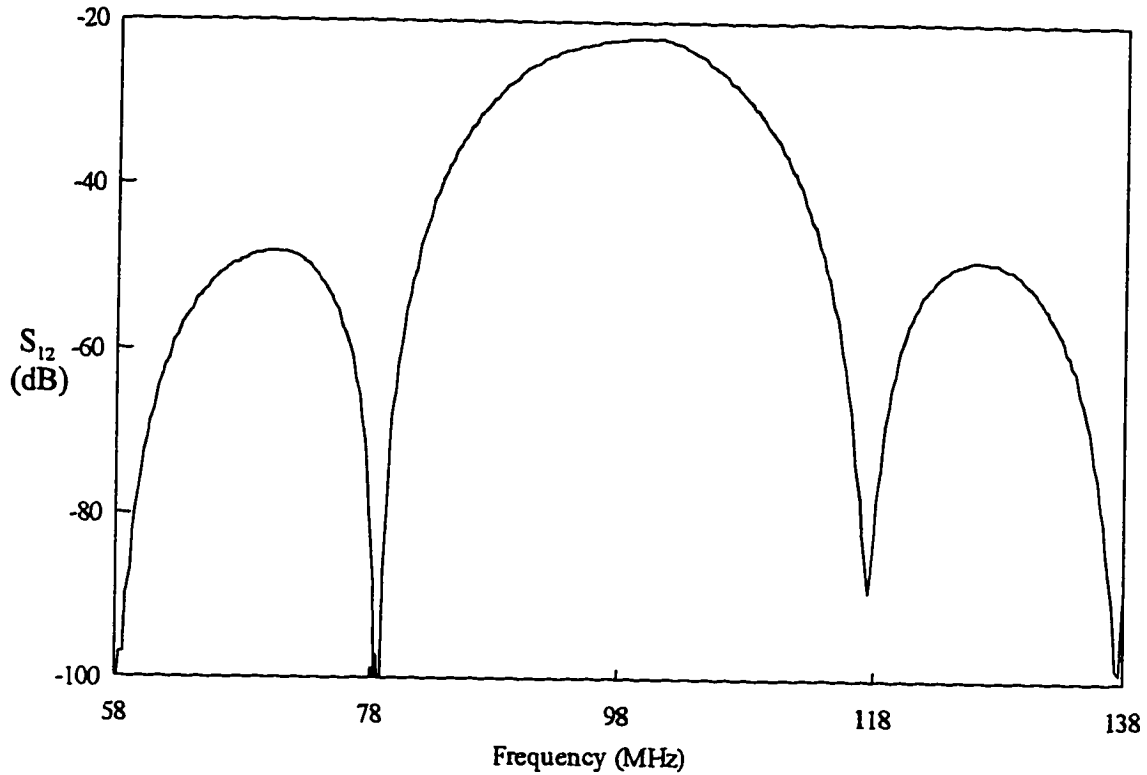


Figure 29. Multilevel device frequency response. Unmatched response of a (nominally) 100 MHz delay line using multilevel transducers with interleaved electrodes on YZ LiNbO₃. Electrode width is 17.44 μm .

Parameter extraction was performed on typical devices of each type. Extracted transducer equivalent circuit parameters are presented below for the 50 MHz control device shown in Figure 28 and for a 100 MHz multilevel device with interleaved electrodes similar to that shown in Figure 29. Data obtained as a result of performing parameter extraction on all device types tested is presented throughout this chapter. The process used to obtain this data is analogous to that presented in the following section.

Parameter Extraction

Full S-parameter data was collected for each device over a span wide enough to include the main lobe and at least two sidelobes of the device frequency response. The S_{12} data was previously shown in Figures 28 and 29. This data was measured and collected in dB, then converted into linear format for calculation of device impedance. The real and imaginary parts of the impedance given by equation (13) in Chapter 3 were calculated separately. The transducer parasitic resistance R_t was determined as the constant offset in the real part of Z as shown in Figure 30 for the control devices and in Figure 31 for the multilevel device. For the control device shown, R_t was found to be 7.2Ω , while for the multilevel device, R_t was 5.8Ω . Subtracting R_t from the transducer input impedance yielded $Z_i(\omega)$, which was then inverted to yield the acoustic input admittance $Y_i(\omega)$. A linear fit to the values of $\text{Im}(Y_i(\omega))$ in frequency ranges away from device center frequency was used to extract the total measured capacitance C_{meas} as shown in Figure 32 for the control device and in Figure 33 for the multilevel device. This measured capacitance is the sum of the transducer and bond pad capacitances. Header capacitance was measured directly, and was found to be approximately 0.4 pF for both devices, but in practice C_{header} was calibrated out along with the fixture and hence not included in C_{meas} . An estimate of the substrate equivalent dielectric constant C_s^{eff} was found using equation (14), and the transducer capacitance C_t was calculated using C_s^{eff} in equation (10). For the control device, an effective substrate dielectric constant C_s was calculated as 4.7 pF/cm ,

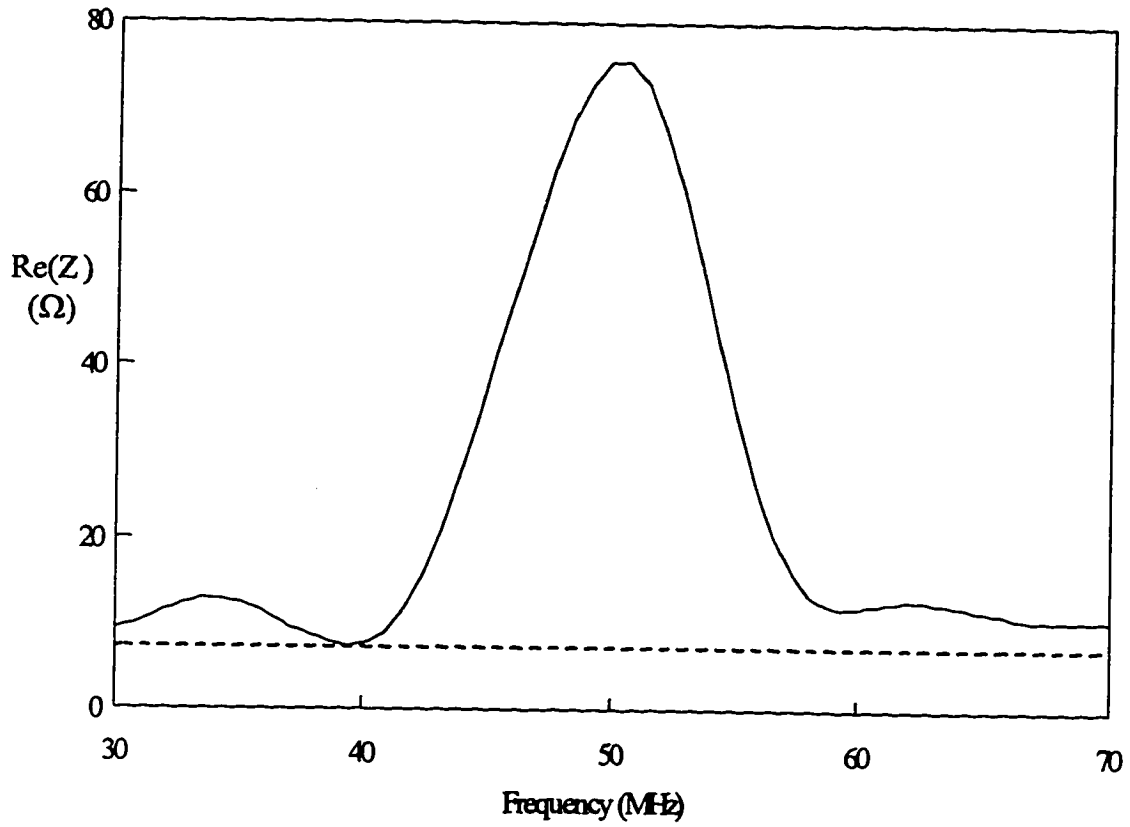


Figure 30. Transducer parasitic resistance extraction for a 50 MHz control device. The horizontal line represents the constant offset $R_t = 7.2 \Omega$.

while for the multilevel device, C_t^{eff} was found to be 11.5 pF/cm. Transducer capacitances were calculated as 7.5 pF for the control device and 18.3 pF for the multilevel device.

Once C_t was determined, the experimental Q_t was calculated at center frequency from the capacitance values and the measured $\text{Re}(Y_t(\omega_c))$ using equation (15). In equation (15), $\zeta = 1.0836$ was used for the control devices with split fingers and a 50% line/period ratio. For the specific multilevel device considered here, the transducer used non-split fingers with a line/period ratio of approximately 100%, and the value used for ζ was 1.0.

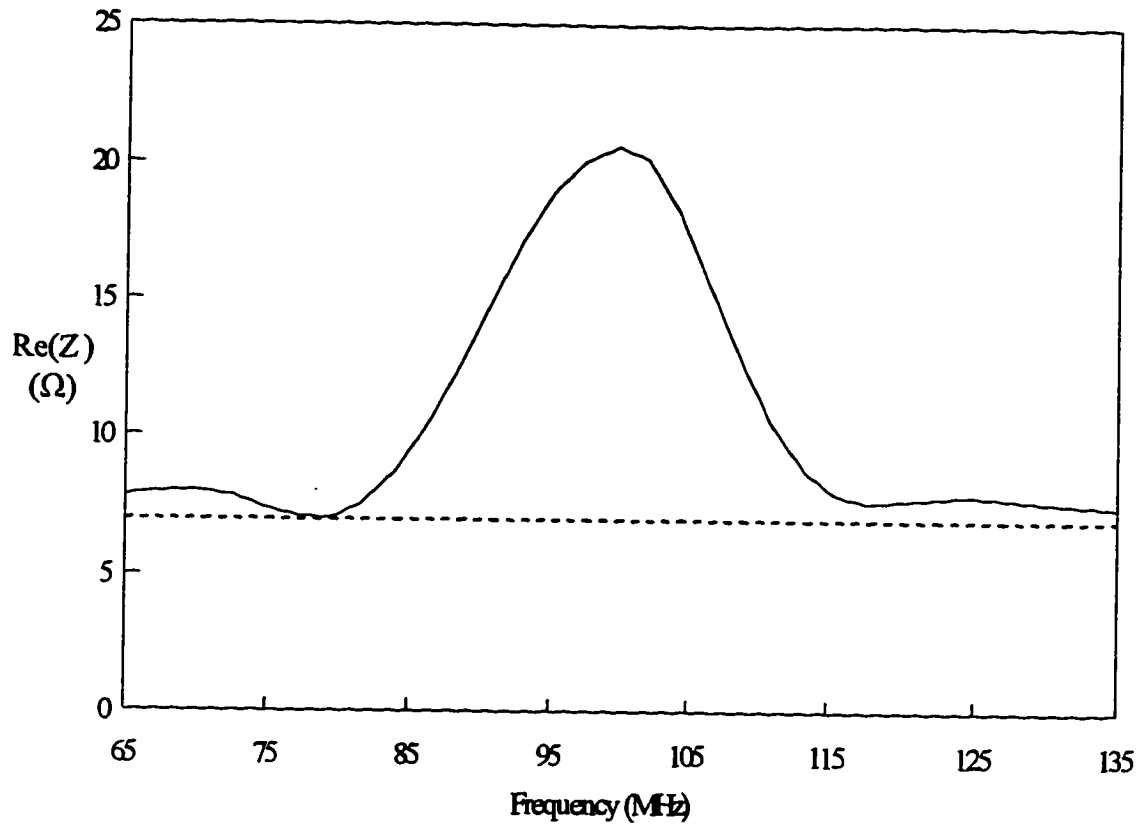


Figure 31. Transducer parasitic resistance extraction for 100 MHz multilevel device. The horizontal line represents the constant offset $R_l = 5.8 \Omega$.

Using equation (15) to solve for k^2 yielded values of $k^2 = 0.045$ for the control devices, in agreement with previously published values for YZ LiNbO₃, and $k^2 = 0.026$ for the interleaved multilevel devices, substantially less than the coupling for the control devices.

Substituting the extracted values of k^2 and C_s into equation (9) yielded a value for transducer center frequency conductance. Using the extracted values of $G_o = G_s(\omega_o)$, C_i , and R_l and equations (1) through (8) and (12) yielded the predictions shown in Figures 34 through 37 for the real and imaginary parts of the input impedance and admittance. The

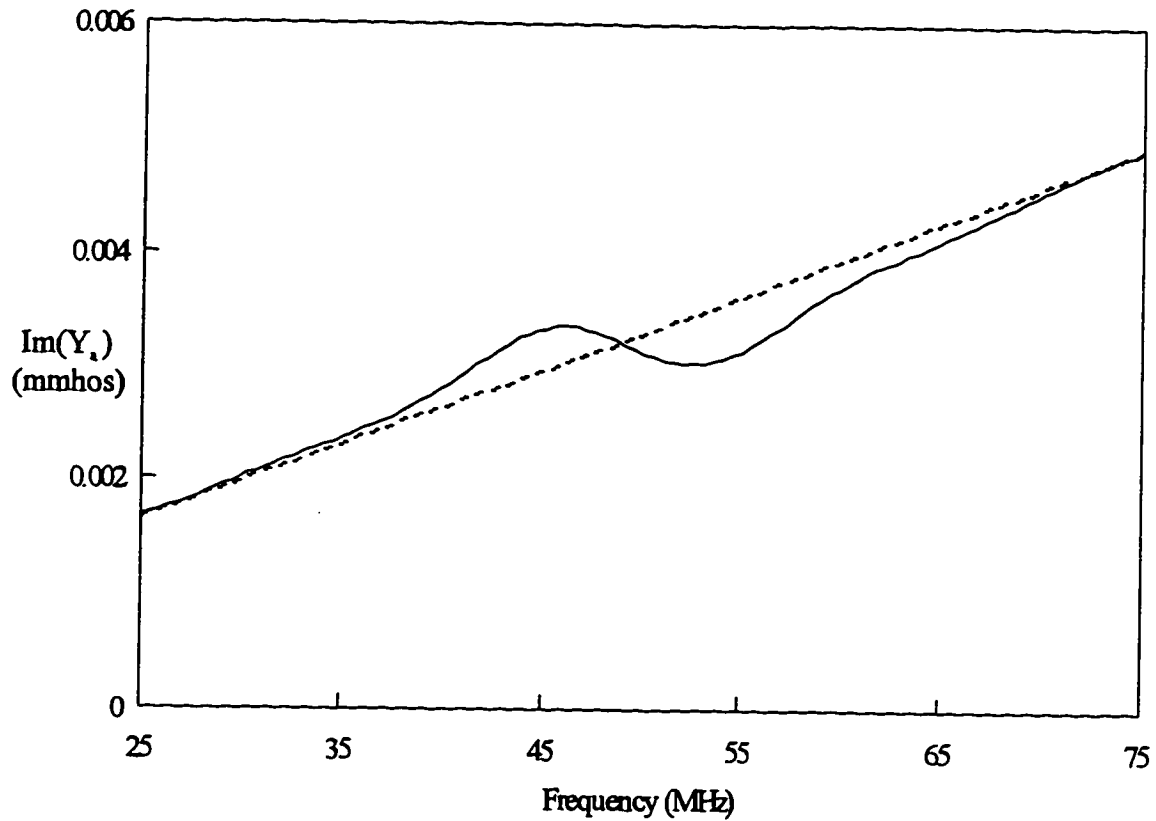


Figure 32. Transducer total capacitance extraction for control device.

relatively good agreement between experimental measurements and this approximate model using the extracted parameters is shown in Figure 34 for the control device impedance and in Figure 35 for the control device admittance, and in Figure 36 for the interleaved multilevel device impedance and in Figure 37 for the interleaved multilevel device admittance.

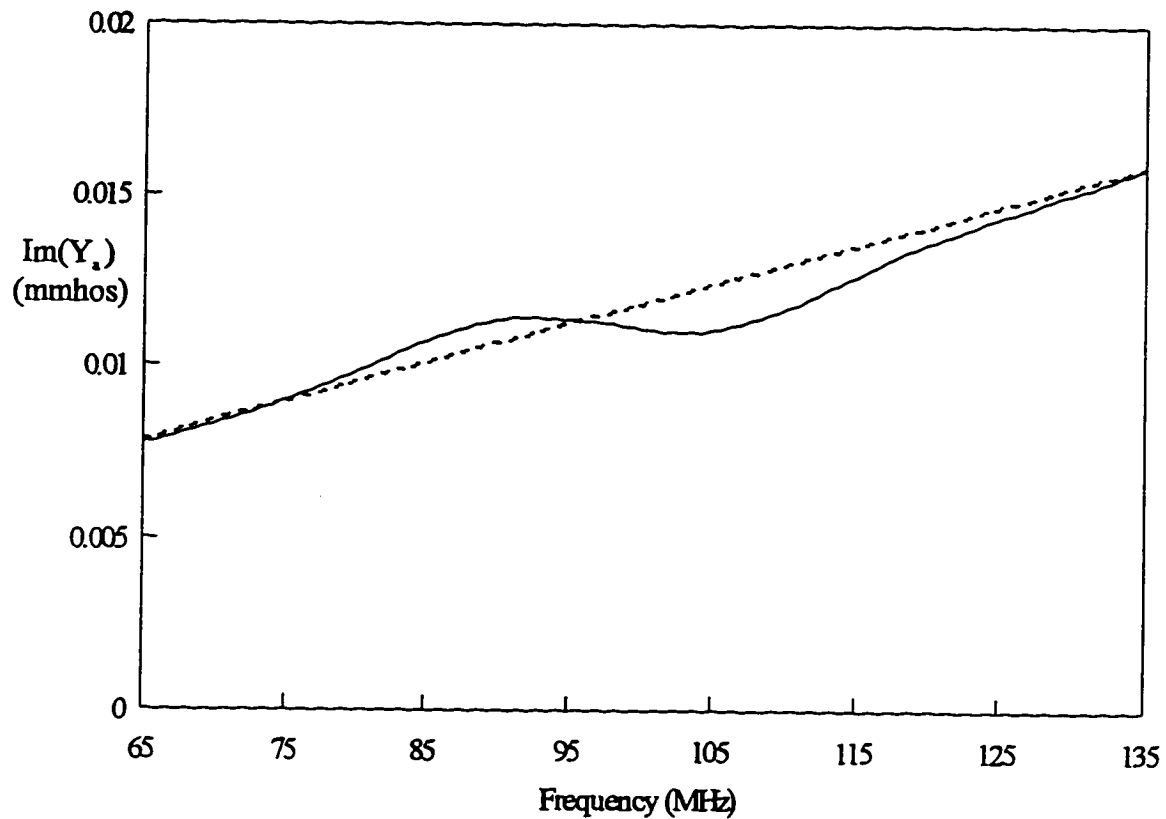


Figure 33. Transducer total capacitance extraction for 100 MHz multilevel device.

Evaluation of Unweighted 500 MHz Devices

The response of a typical unweighted 500 MHz device fabricated with five active taps in a multilevel structure with interleaved upper and lower electrodes is shown in Figure 38. Unmatched insertion loss for this device is approximately 31 dB, and the characteristic $[\sin(x)/x]^2$ response is evident. The time domain response of this device is shown in Figure 39, demonstrating the low levels of reflections internal to the transducer. Ideally, a transducer structure with perfect half-wavelength fingers and no gaps should be internally reflectionless. Figure 39 shows that in this device, all reflections are suppressed by more than 63 dB relative to the main SAW response, with the exception of the triple

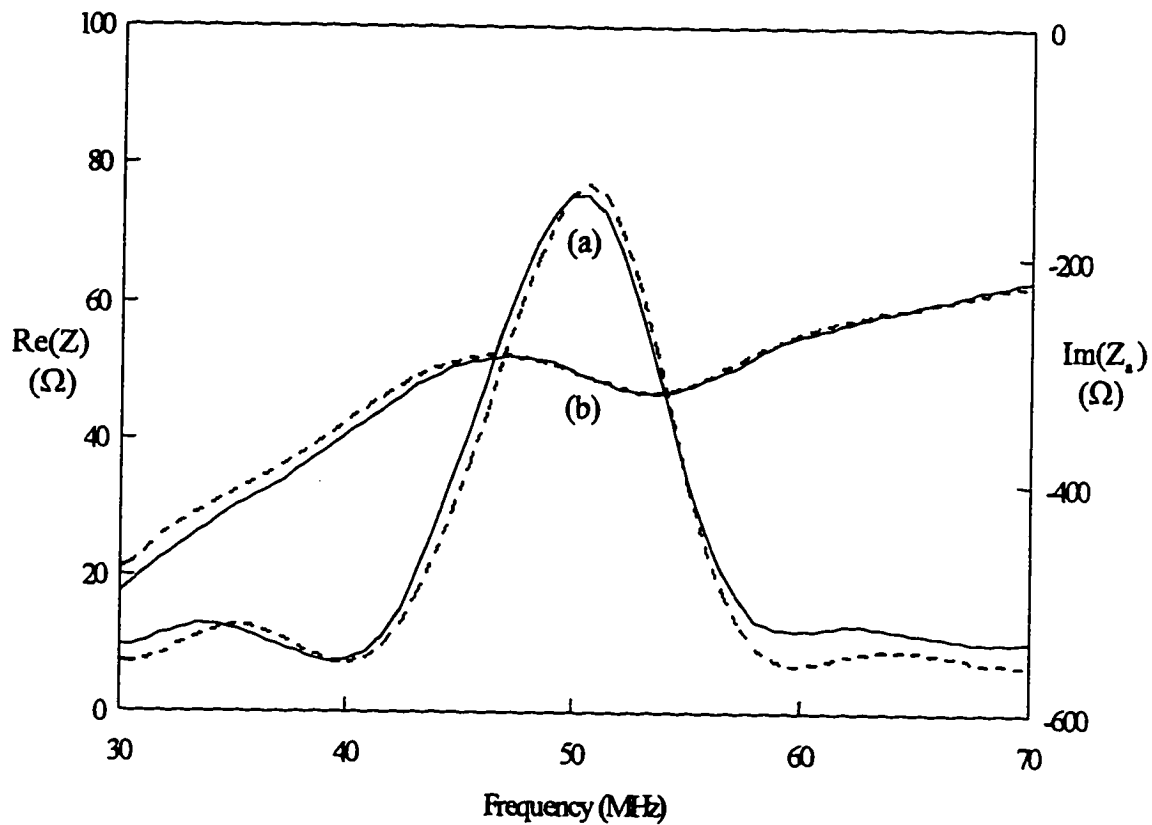


Figure 34. Comparison of measured transducer impedance and impedance predicted based on equivalent circuit parameter extraction and lumped equivalent circuit model for 50 MHz control device. Solid lines represent experimental data, dashed lines are calculated using model. (a) $Re(Z(\omega))$, (b) $Im(Z_s(\omega))$.

transit response, which is 55 dB below the main response. Triple transit is a response which is the result of the SAW traveling from the input transducer to the output transducer, a wave being regenerated back towards the input transducer, and another wave being launched toward and subsequently received by the output transducer. Since triple transit is caused primarily by regeneration effects, the presence of this signal is not

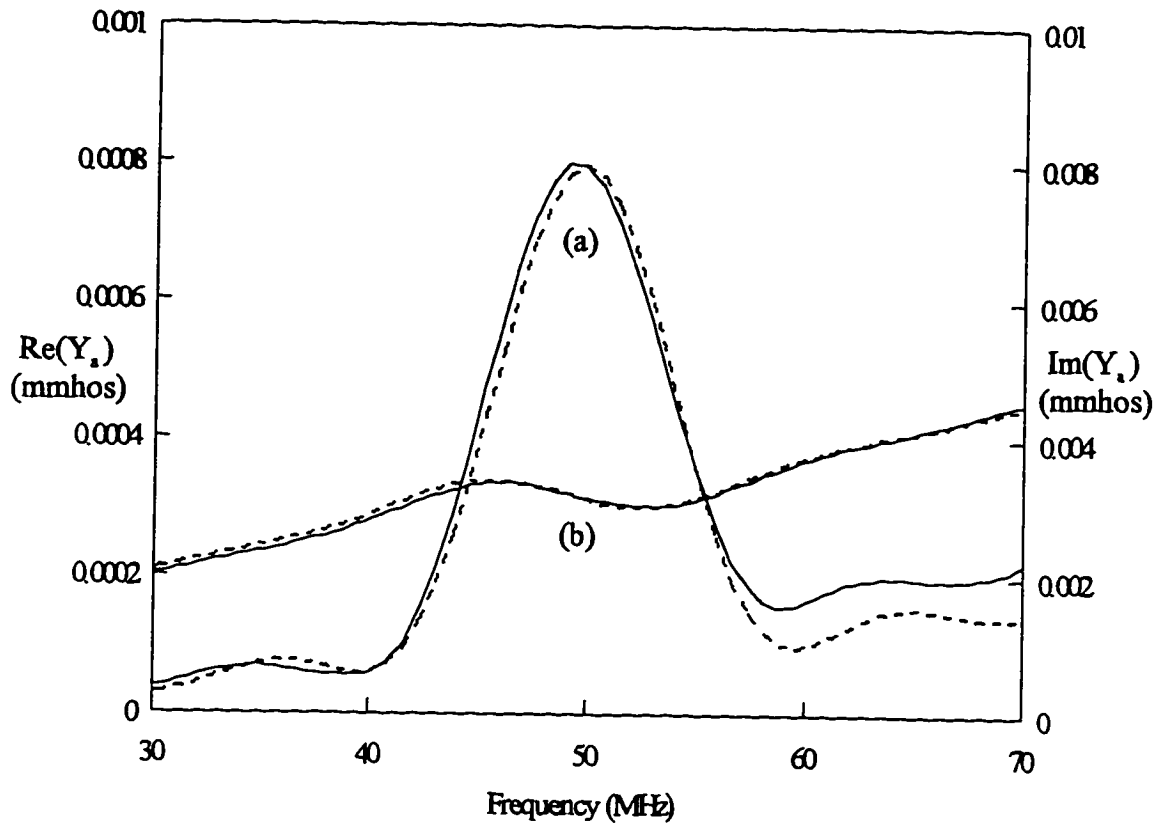


Figure 35. Comparison of measured transducer admittance and admittance predicted based on equivalent circuit parameter extraction and lumped equivalent circuit model for 50 MHz control device. Solid lines represent experimental data, dashed lines are calculated using model. (a) $\text{Re}(Y_s(\omega))$, (b) $\text{Im}(Y_s(\omega))$.

indicative of reflections internal to the transducers. Internal reflections will generally result in time domain spurious responses and a ripple in the device frequency response. Figure 39 verifies the expected low level of reflections internal to the transducers in the half-wavelength electrode multilevel device structure.

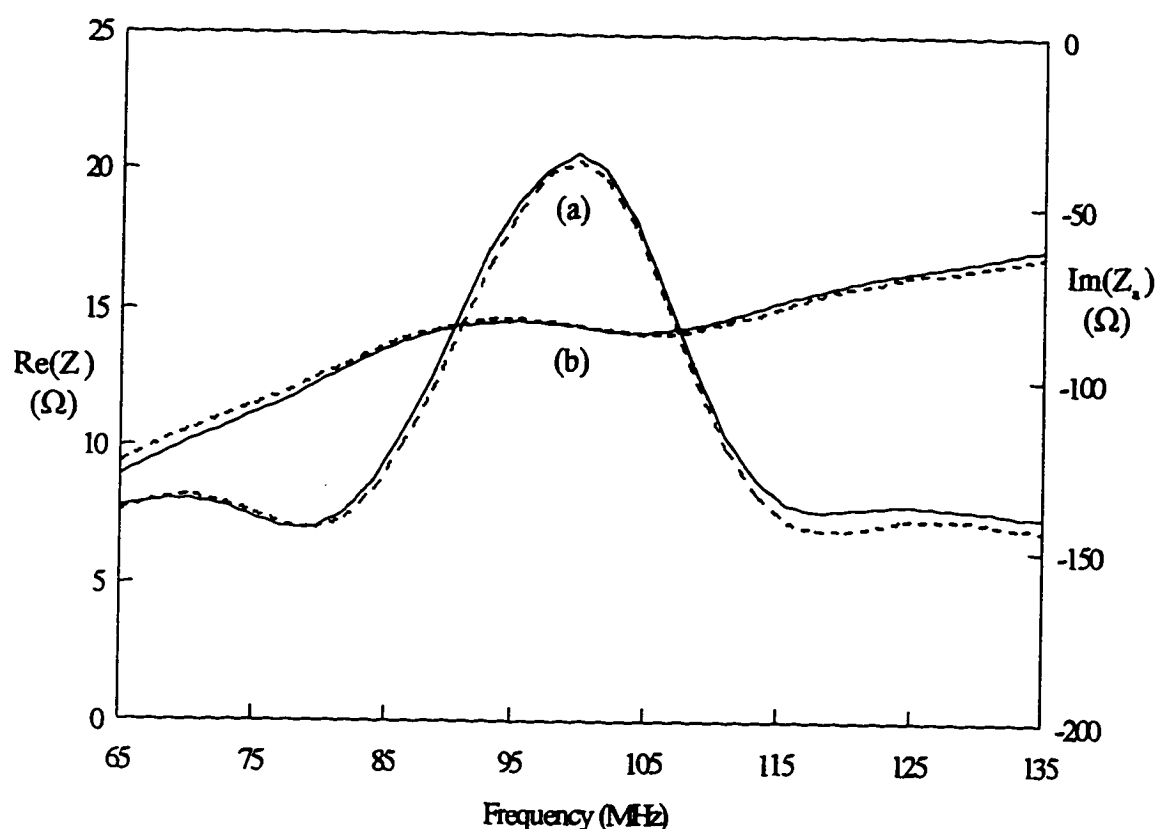


Figure 36. Comparison of measured transducer impedance and impedance predicted based on equivalent circuit parameter extraction and lumped equivalent circuit model for 100 MHz multilevel device. Solid lines represent experimental data, dashed lines are calculated using model. (a) $Re(Z(\omega))$, (b) $Im(Z_s(\omega))$.

Comparison of Solid and Interleaved Upper Electrodes

A multilevel device similar to that which yields the response shown in Figure 38 was fabricated with a solid pad as an upper electrode instead of interleaved electrode fingers. The response of this device is shown in Figure 40. Note the smearing of the response and the slightly higher insertion loss caused by the modified upper electrode.

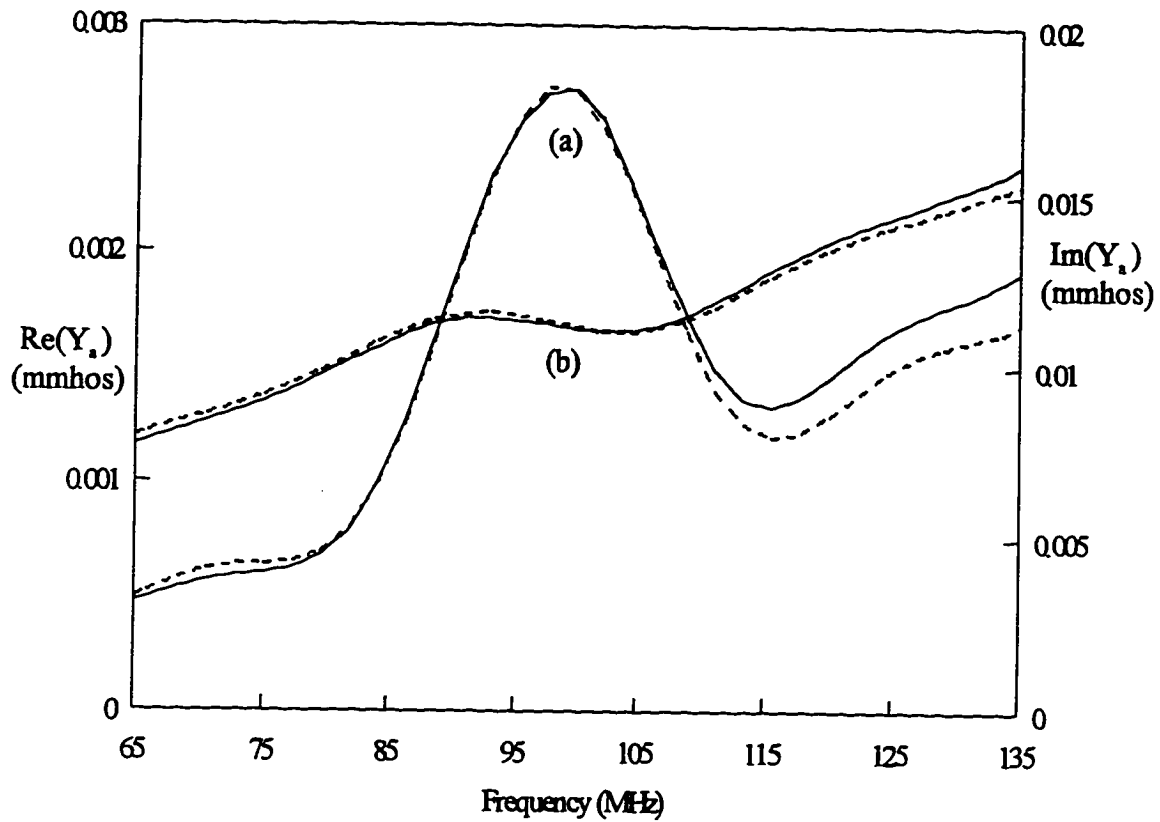


Figure 37. Comparison of measured transducer admittance and admittance predicted based on equivalent circuit parameter extraction and lumped equivalent circuit model for 100 MHz multilevel device. Solid lines represent experimental data, dashed lines are calculated using model. (a) $\text{Re}(Y_s(\omega))$, (b) $\text{Im}(Y_s(\omega))$.

These effects are the result of the solid upper electrode distorting the electric field, concentrating the field lines between the bottom level electrode fingers and the upper electrode pad. This reduces the electric field density in the substrate, and thereby reduces the effective electro-acoustic coupling, leading to the observed increase in loss. RF feed-through also increases with a solid upper electrode, resulting in response smearing.

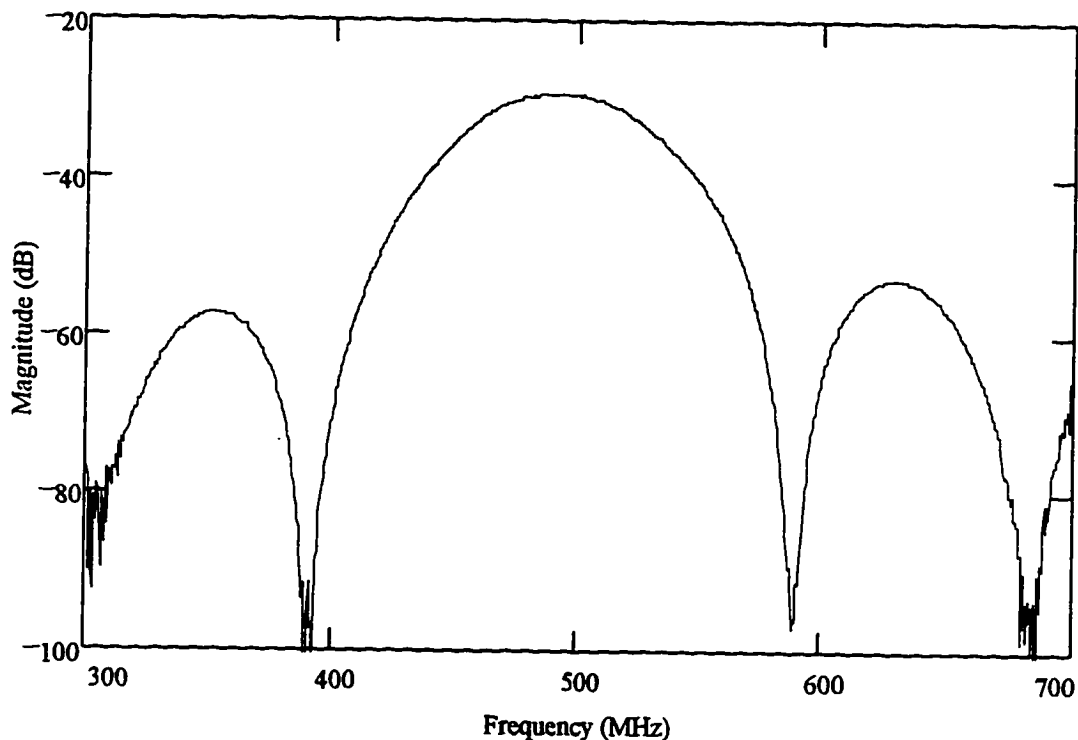


Figure 38. Frequency response of a 500 MHz device using unweighted multilevel transducers with interdigitated electrodes.

Evaluation of Weighted 500 MHz Devices

The response of a 500 MHz device consisting of one apodized and one unweighted transducer is shown in figure 41. The unmatched device insertion loss is approximately 25 dB, and the ultimate rejection is slightly over 45 dB. Although the near-in sidelobes have been substantially degraded relative to the 45 dB sidelobe level of the ideal device frequency response, the steep shape factor observed down to approximately 25 dB and the relatively flat passband response are quite encouraging for a device designed using

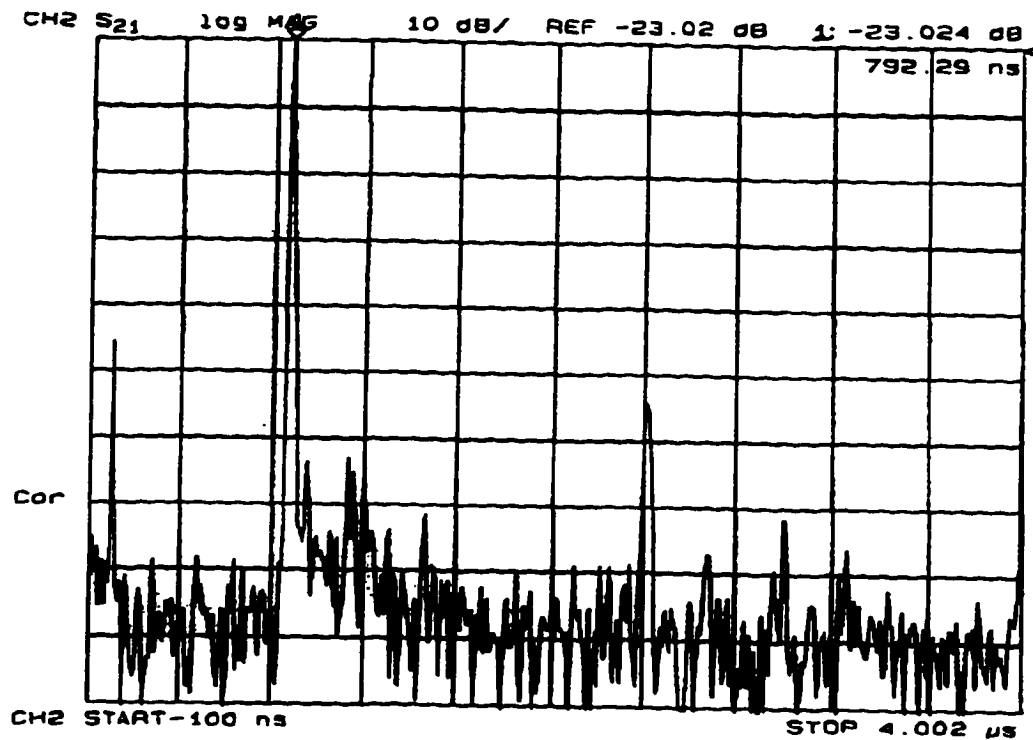


Figure 39. Time domain response demonstrating low levels of reflections internal to the transducer. Frequency response of this device is shown in Figure 38.

computer aided design tools for conventional single level SAW transducer structures and fabricated using multilevel half-wavelength transducers. It should be noted that gating of RF feedthrough was required to obtain the responses shown in figures 38, 40, and 41.

Parameter Extraction for 500 MHz Devices

Equivalent parameter extraction was performed on the unweighted 500 MHz multilevel devices, and the results are presented in Figures 42 and 43. As for the 100

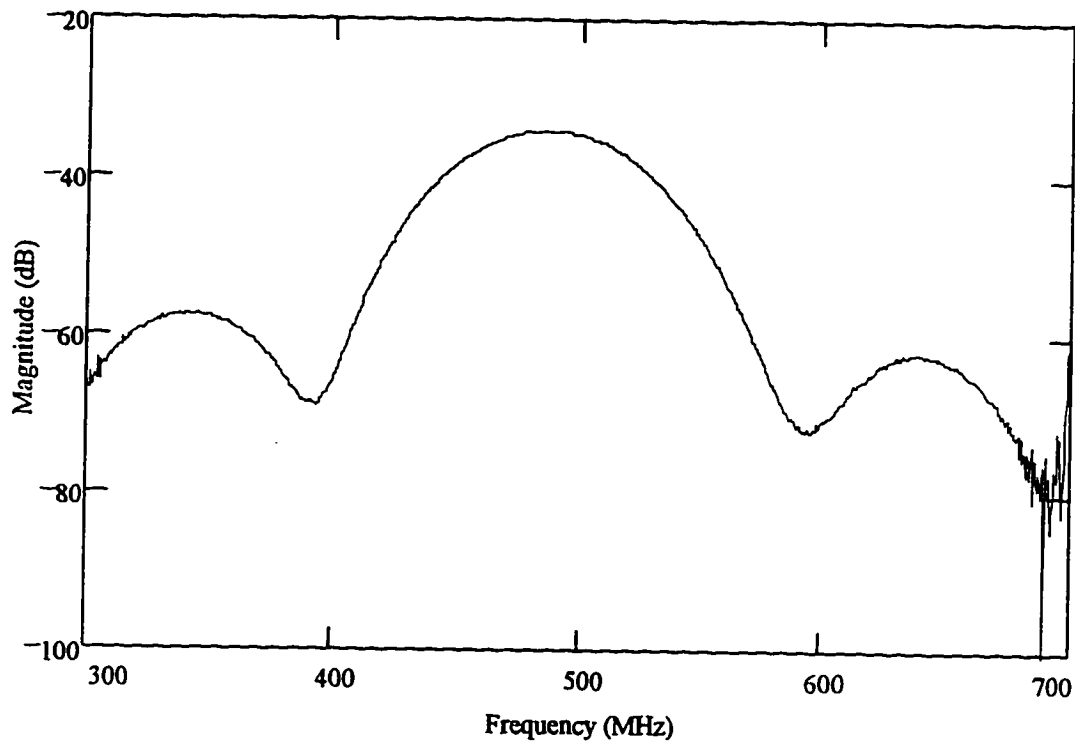


Figure 40. Frequency response of a 500 MHz device using unweighted transducers with a solid upper electrode pad.

MHz multilevel devices, the parameter extraction process proceeds as previously presented for the 500 MHz unweighted devices with interleaved upper and lower electrode fingers. For a typical device with an intermediate silicon nitride dielectric layer 960 Å thick, aluminum electrodes approximately 900 Å thick, and metallization ratio of 80%, the extracted transducer parasitic resistance R_t is approximately 8 Ω. For the same device, the transducer capacitance is found to be 0.833 pF, and the effective substrate dielectric constant is 6.18 pF/cm. The extracted electro-acoustic coupling is 0.0269.

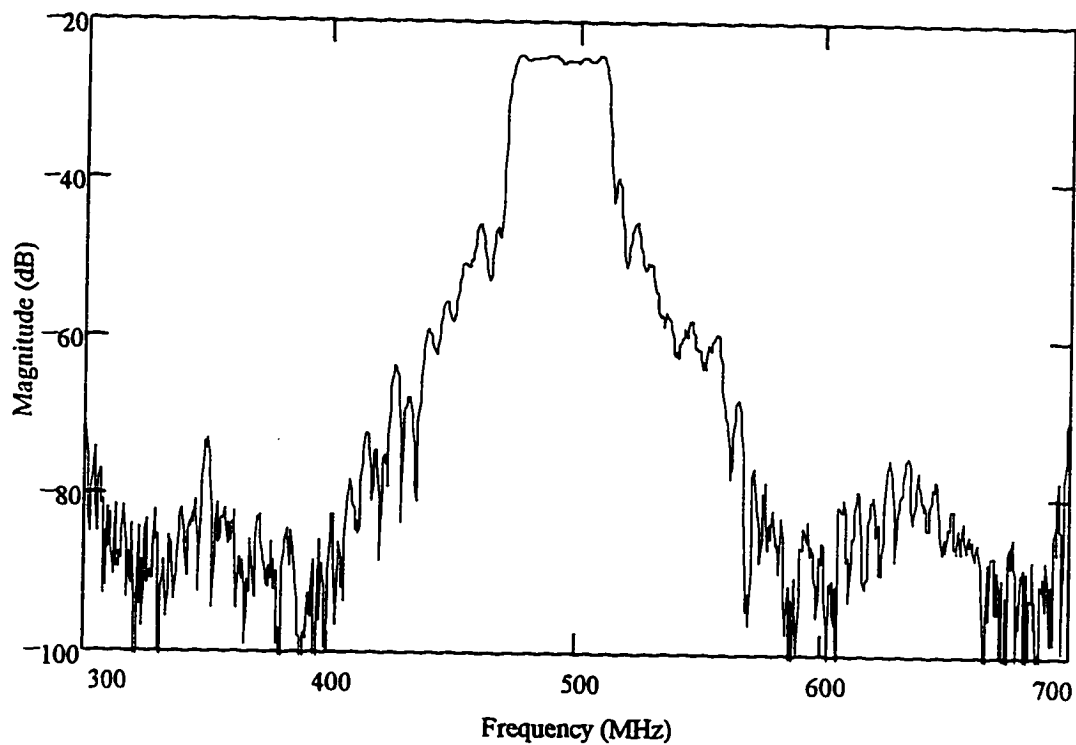


Figure 41. Unmatched response of 500 MHz device using one apodized transducer and one unweighted transducer.

Using these extracted parameters in the lumped equivalent circuit model, the predicted transducer impedances and admittances were calculated. These calculations yield results which agree fairly closely with experimental results, as shown in Figure 42.

Parameter extraction was also performed on the unweighted multilevel transducers with solid upper electrodes. Because these devices showed frequency responses which were distorted relative to those devices with interleaved upper and lower electrodes, the

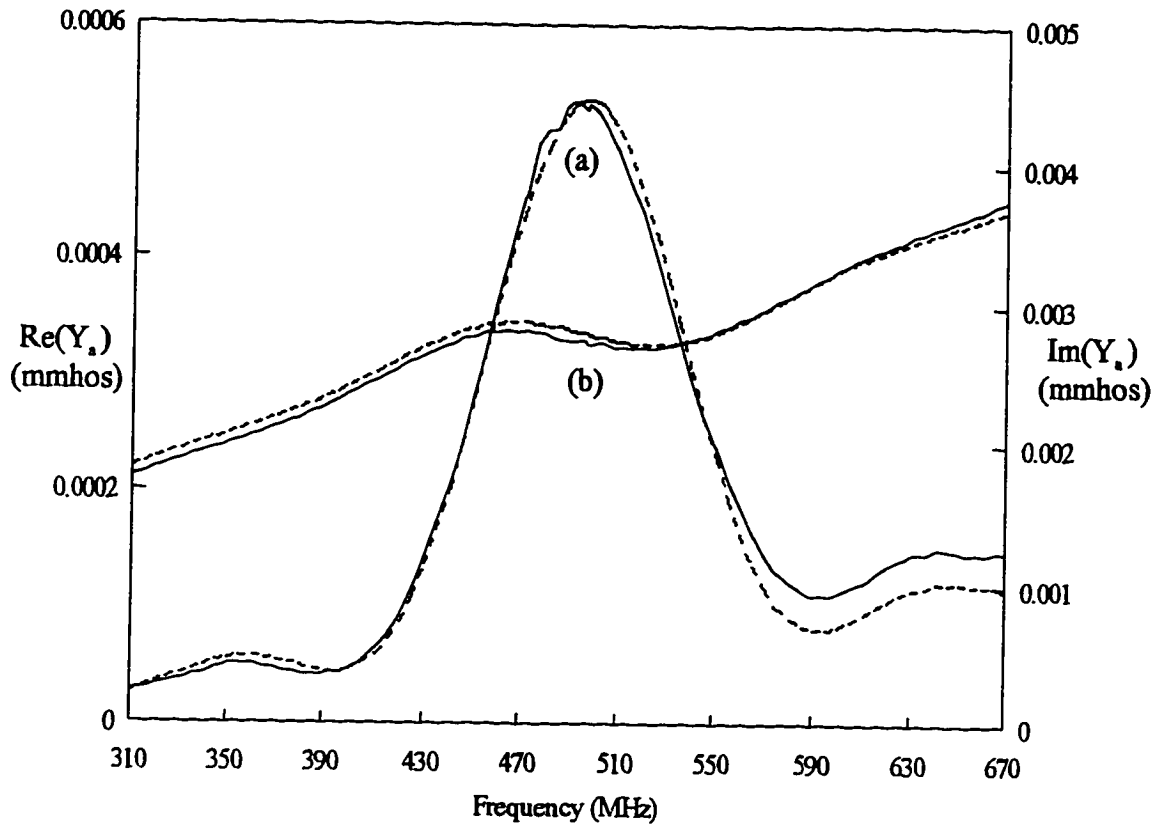


Figure 42. Comparison of predicted and experimental admittance for 500 MHz device using unweighted multilevel transducers with interleaved upper and lower electrode fingers. Solid lines represent experimental data, dashed lines are calculated using model. (a) $\text{Re}(Y_s(\omega))$, (b) $\text{Im}(Y_s(\omega))$.

solid electrode structure is less desirable in practice. This extraction process was done to illustrate the application of the process to an additional unusual structure.

Figure 43 compares the experimental values for the real part of transducer impedance and the imaginary part of the transducer admittance for 500 MHz devices using unweighted multilevel transducers with interleaved upper and lower electrode fingers and

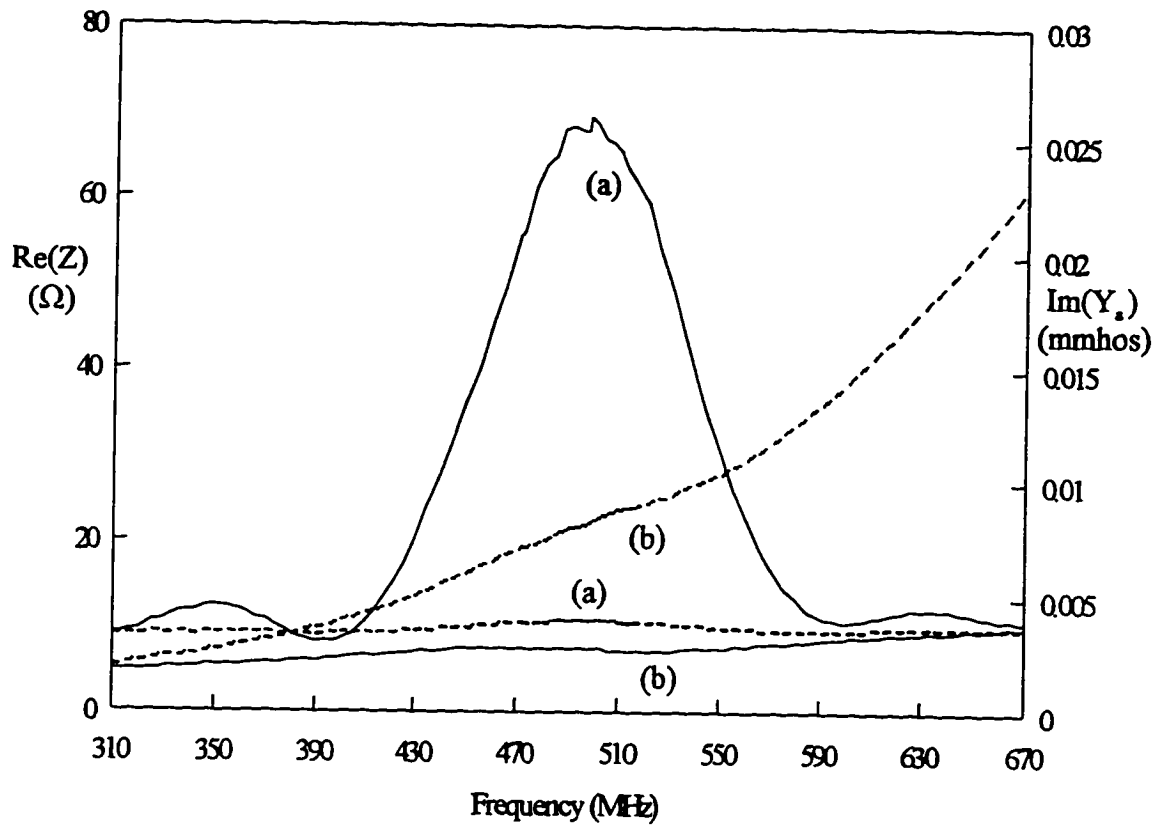


Figure 43. Comparison of experimental values for the real part of transducer impedance and the imaginary part of the transducer admittance for 500 MHz devices using unweighted multilevel transducers with interleaved upper and lower electrode fingers and using solid metal upper electrodes. Solid lines represent experimental data for a multilevel device with interleaved upper electrodes, dashed lines are experimental data for similar device with a solid upper electrode. (a) $\text{Re}(Z(\omega))$, (b) $\text{Im}(Y_s(\omega))$.

for unweighted multilevel transducers using solid metal upper electrodes. The transducer parasitic resistance for the transducer with the solid upper electrode is approximately

9.3 Ω , close to that for the interleaved multilevel transducer. This is expected, since the metallizations used were fabricated in identical fashion, and were of equal thickness. It is obvious from the responses in Figure 43 that the solid upper electrode causes substantially higher transducer capacitance than the interleaved upper electrodes, as would be expected from this transducer structure. The solid electrode transducer has an extracted capacitance of approximately 10.2 pF, more than an order of magnitude larger than that of the 500 MHz interleaved multilevel transducer presented previously. The effective coupling for the solid electrode structure is approximately $k^2 = 0.0062$, roughly four times smaller than that for the interleaved transducer.

The real and imaginary parts of the predicted and experimental transducer admittance for the multilevel transducer with the solid upper electrode are compared in Figure 44. While the parameter extraction technique does not break down entirely, it does yield results which are substantially less accurate than those obtained for transducer structures which are nominally more like interdigital transducers.

Parameter extraction was performed on the multilevel apodized transducer used in the 500 MHz device whose frequency response is shown in Figure 41. Although the parameter extraction and equivalent circuit modeling process does not allow for apodization to be taken into account, reasonably accurate parameters can be extracted by using an effective number of taps during extraction. Because one transducer in this device was unweighted and one apodized, extraction was performed on each, and the resulting parameters compared. For the unweighted transducer with an intermediate silicon nitride layer 960 Å thick and aluminum electrodes approximately 900 Å thick, the transducer

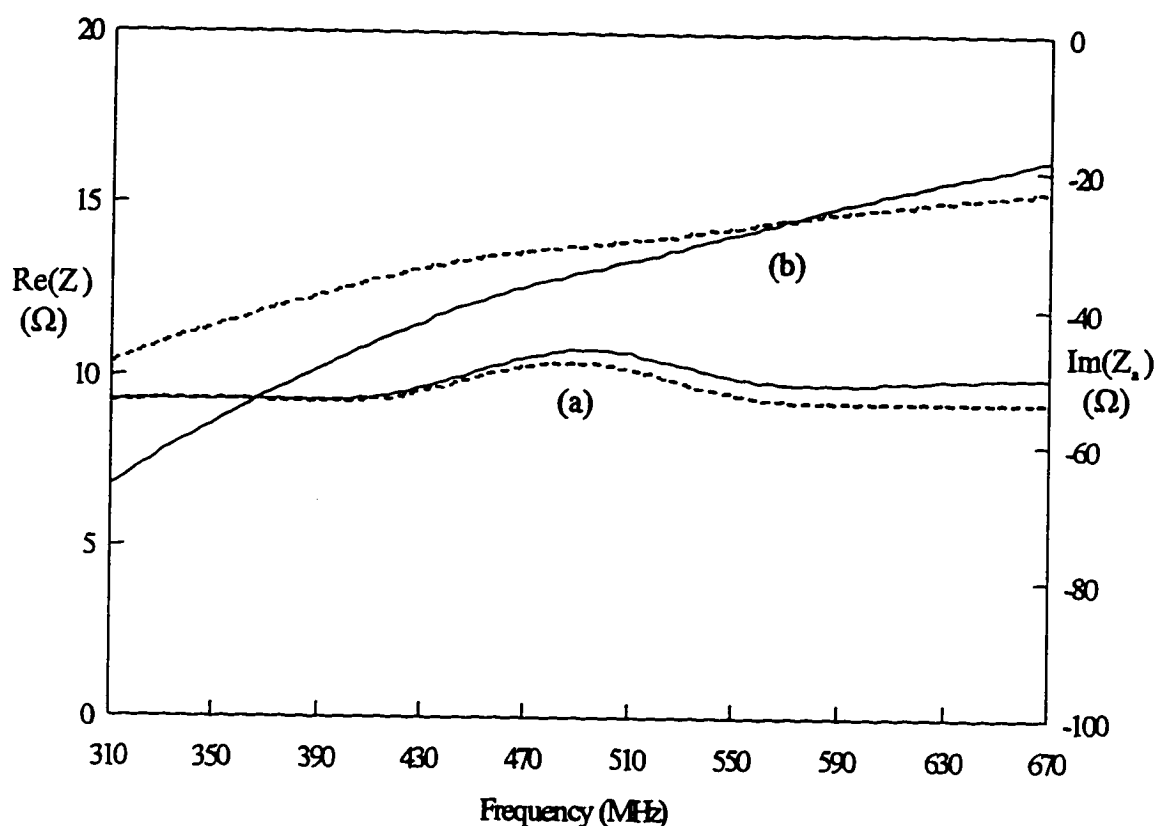


Figure 44. Comparison of predicted and experimental impedance for 500 MHz device using unweighted multilevel transducers with solid upper electrode. Solid lines represent experimental data, dashed lines are calculated using model. (a) $\text{Re}(Z(\omega))$, (b) $\text{Im}(Z_s(\omega))$.

parasitic resistance R_t was extracted as 6.1Ω , and the transducer capacitance is found to be 0.58 pF . For the apodized transducer on the same device, the transducer parasitic resistance R_t is extracted as 3.5Ω , and the transducer capacitance is found to be 2.48 pF . The effective substrate dielectric constant is 4.4 pF/cm , and the electro-acoustic coupling is found to be 0.033 . Values extracted are for a device with a metallization ratio of 80%.

Substrate Equivalent Dielectric Constant

The effective substrate equivalent dielectric constant, C_s^{eff} , was extracted for devices fabricated with a range of silicon nitride film thicknesses. The average value of C_s extracted for control devices fabricated using single level split finger transducers at 50 MHz with no nitride layers was 4.7 pF/cm. This value is in fairly good agreement with published values for YZ LiNbO₃ [53, 59]. Figure 45 shows the extracted C_s^{eff} data for devices with silicon nitride layers ranging from 500 Å to 3350 Å thick. The horizontal line is a best fit to the observed data, and indicates an approximate value of $C_s^{\text{eff}} = 11.81 \text{ pF/cm}$. The value of C_s^{eff} extracted for the transducer structures considered here is considerably larger than that of a single level transducer with 50% metallization ratio. Because the electrodes in the multilevel transducers are approximately half-wavelength, the proximity of adjacent electrodes causes a substantial increase in the inter-electrode capacitance [53].

Because thicker intermediate dielectric layers were expected to increase the distance between adjacent electrodes and reduce the transducer capacitance C_t for a given number of electrodes and a given aperture, and hence reduce the effective substrate equivalent dielectric constant C_s^{eff} , finding that C_s was independent of film thickness for the range of film thicknesses considered was initially surprising. However, detailed consideration of the transducer structure provides an explanation for the observed phenomenon. Because a metal thickness of 1500 Å was used for these devices, it can be seen that for silicon nitride film thicknesses below 1500 Å, the silicon nitride film will be primarily deposited on top of and between the metal electrodes, with a thin film providing step coverage. The upper level metal electrodes will then be deposited in very close

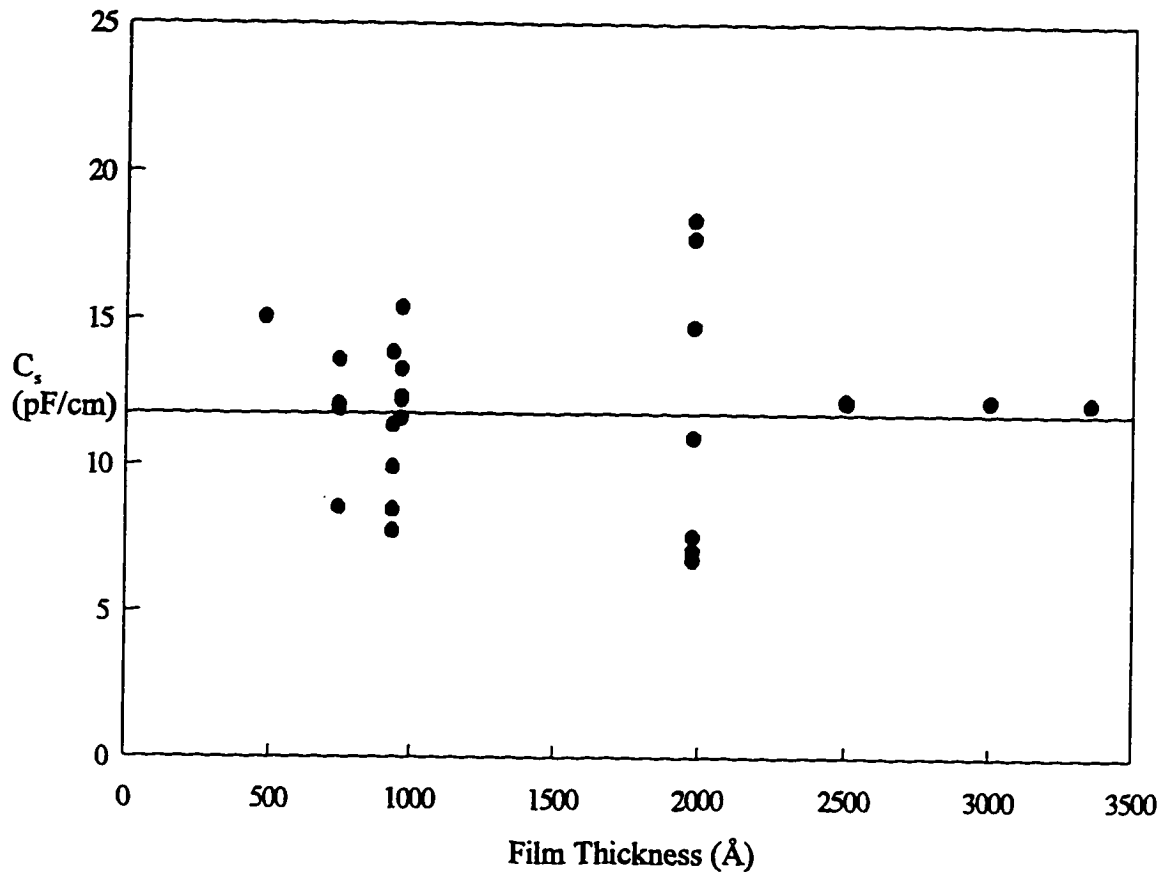


Figure 45. Substrate equivalent dielectric constant C_s for various Si_3N_4 film thickness normalized to a metallization ratio of approximately 100%.

proximity to the lower electrodes. The distance between the upper and lower metal electrodes will not increase substantially with increasing nitride film thickness until the films are more than 1500 Å thick. For thicker silicon nitride films, the effects of increasing film thickness should be more evident. However, most of the devices fabricated with nitride films over 2000 Å thick were 100 MHz devices, with electrodes 17.44 μm wide. Increasing the dielectric film thickness by 1000 Å would correspond to changing the electrode width by approximately 0.6%. Because changes of this magnitude are at or

below the resolution of the process used to determine the device line to space ratios, any variation in C_s^{eff} due to changes in dielectric film thickness would be indeterminate due to measurement uncertainty.

Due to the fact that the devices fabricated had metallization ratios ranging from 70% to 100%, the data shown in Figure 45 has been compensated for the variation in metallization ratio to yield the equivalent C_s^{eff} at approximately 100% metallization. The variation in normalized capacitance C_n with metallization ratio is given by [55]

$$C_n = \frac{P_{-0.5}(\cos(\pi\eta))}{P_{-0.5}(-\cos(\pi\eta))} \quad (34)$$

where η represents the metallization ratio and P is a Legendre function [65]. Since this normalized capacitance C_n is not well defined at $\eta = 1.0$, an approximation was made which normalized experimentally extracted values of C_s to $C_n(0.995) = 3.2$ pF/cm. For example, if a particular device had $\eta = 0.9$, which corresponds to $C_n = 1.85$ pF/cm, the measured value of C_s^{eff} would be normalized using

$$C_s^{eff}(\eta \approx 1.0) = C_s^{eff}(\eta = 0.9) \left[\frac{3.2}{1.85} \right] \quad (35)$$

The relatively large standard deviation in the normalized data presented in Figure 45, $\sigma = 2.97$ pF/cm, is due primarily to uncertainties in determining accurate device metallization ratios.

Effective Coupling

The electro-acoustic coupling factor, k^2 , was extracted for control devices and as a function of silicon nitride film thickness. The average value extracted for control devices fabricated using single level split finger transducers at 50 MHz with no nitride layers was 0.045, in fairly good agreement with published values for YZ LiNbO₃ [53, 59]. A decrease in the coupling efficiency was expected when the metal fingers are offset from the crystal surface by a dielectric layer such as Si₃N₄. What was observed was a frequency dependent decrease of k^2 from the free surface YZ LiNbO₃ value with the introduction of a thin (480 Å) Si₃N₄ layer. As the nitride thickness is increased, the coupling decreases further.

A simple capacitance-based model for the variation in coupling with changes in nitride film thickness was developed, and is shown schematically in Figure 46. This model assumes that the coupling, which is a measure of the power transmitted from the electrical signal into the acoustic wave, can be described by the interaction of capacitances within the multilevel transducer structure. As shown in Figure 46, this model assumes three components of capacitance in the transducer structure. Assuming the electric fields between the upper and lower electrodes intersect the substrate surface approximately normally, the surface of the substrate under the upper electrode and dielectric film can be approximated as an equipotential region, and a parallel plate capacitance C_e can be postulated. C_e represents the standard inter-electrode capacitance, which is dependent on the lateral separation of the electrode edges. C_f represents a fringing capacitance through the nitride film between the upper and lower electrodes. Considering position A on the

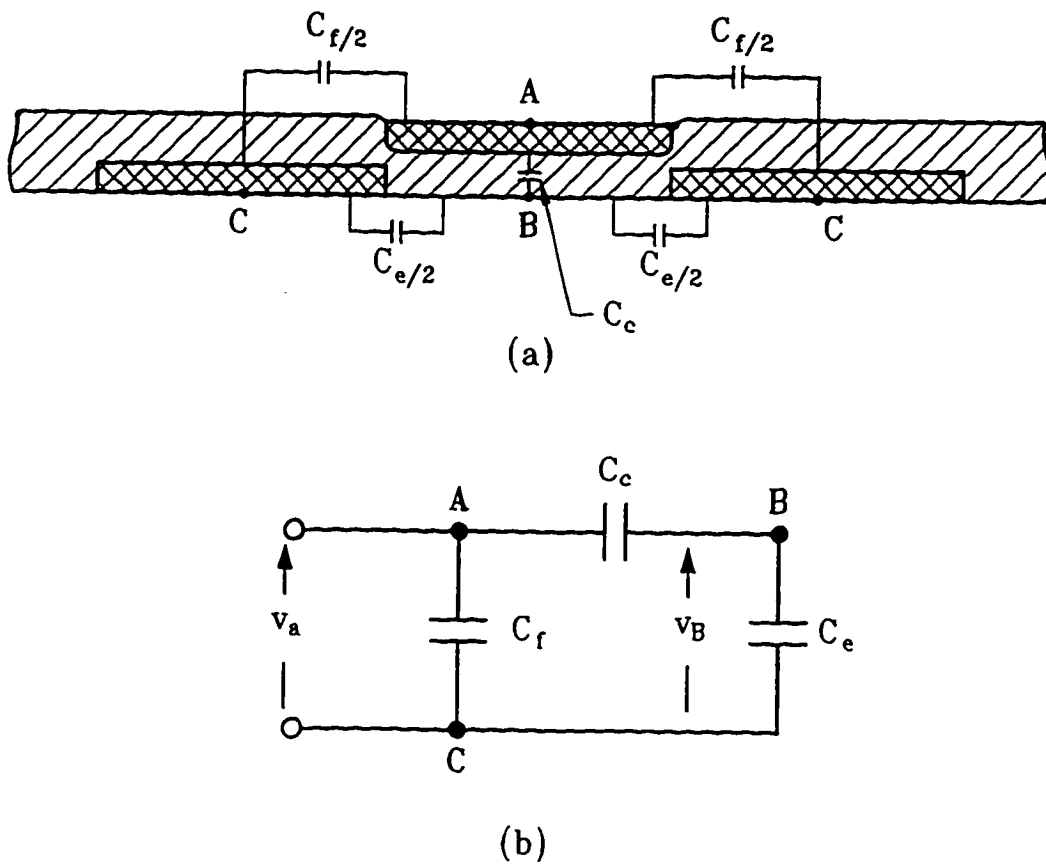


Figure 46. Model for dependence of k^2 on dielectric layer thickness. (a) Schematic of general capacitance model, (b) Equivalent circuit representation of (a).

upper electrode as the insertion point for electrical energy, and position B on the substrate surface as the position at which a potential is induced to launch the acoustic wave, the capacitances which join A and B can be represented by the circuit shown in Figure 46 (b).

Coupling is then proportional to the square of the ratio of the voltage at the surface, V_A to the voltage at the upper electrode, V_B ,

$$k^2 \propto \left(\frac{V_B}{V_A} \right)^2. \quad (36)$$

This ratio is independent of the fringing capacitance C_f and coupling can be written in terms of the capacitances as

$$k^2 \propto \left(\frac{C_c}{C_c + C_e} \right)^2. \quad (37)$$

Each of the capacitances in equation (37) varies with the metallization ratio η , and because an increase in the dielectric film thickness changes the edge-to-edge separation of adjacent electrodes, this can be viewed as effectively varying the metallization ratio. If the period p is the center-to-center separation of adjacent electrodes, and l_m is the width of the metal electrode, then the metallization ratio η is (l_m/p) . The effective metallization ratio for a given dielectric film thickness h can be approximated by

$$\eta_{eff} \approx \frac{\eta p - h}{p} = \eta - \frac{2h}{\lambda} \quad (38)$$

where $p = \lambda/2$ has been substituted for the multilevel transducers under consideration.

Now, the standard inter-electrode capacitance C_e can be written as a function of η_{eff} as follows

$$C_e(\eta_{eff}) = (\epsilon_o + \epsilon_p^T) \left[\frac{P_{-0.5}(\cos(\pi\eta_{eff}))}{P_{-0.5}(-\cos(\pi\eta_{eff}))} \right] \quad (39)$$

where P represents the Legendre function.

The parallel plate capacitance C_c can be approximated, per unit electrode length, by

$$C_c(h, \eta) = \frac{\epsilon_{film}}{2h} \eta \lambda \quad (40)$$

where $p = \lambda/2$ has been assumed again. Substituting equations (39) and (40) into equation (37) for k^2 , we obtain

$$k_{eff}^2 \propto \left[1 + \left(\frac{\epsilon_o + \epsilon_p^T}{\epsilon_{film}} \right) \left(\frac{2h}{\eta \lambda} \right) \left(\frac{P_{-0.5}(\cos(\pi \eta_{eff}))}{P_{-0.5}(-\cos(\pi \eta_{eff}))} \right) \right]^{-2} \quad (41)$$

Using values for YZ lithium niobate and silicon nitride of $\epsilon_p^T = 51 \epsilon_o$ and $\epsilon_{film} = 7.5 \epsilon_o$, respectively [53, 66], yields

$$\left(\frac{\epsilon_o + \epsilon_p^T}{\epsilon_{film}} \right) = \left(\frac{1+51}{7.5} \right) = 6.93 \quad (42)$$

Calculating the effective coupling as a function of nitride film thickness for frequencies of 100 MHz, 500 MHz, and 1.8 GHz on YZ lithium niobate yields a family of curves, which are plotted with the 100 MHz and 500 MHz experimental data in Figure 47. As can be seen, good correlation is obtained between the experimental data and the values of k^2 predicted by the model described above. Because the coupling is extracted from the measured transducer Q (Q_t) as described in Chapter 3, and Q_t is proportional to the normalized Q (Q_n) which varies with metallization ratio according to [55]

$$Q_n \propto \frac{1}{4} [P_{-0.5}(-\cos(\pi \eta)) P_{-0.5}(\cos(\pi \eta))] \quad (43)$$

it is once again necessary to normalize the raw extracted values of k^2 to the effective value at approximately 100% metallization. Since k^2 is inversely proportional to Q_e , the extracted k^2 data was normalized to $Q_n(>0.99) = 1$. For example, if a particular device had $\eta = 0.9$, which corresponds to $Q_n = 1.91$, the measured value of k^2 would be normalized using

$$k^2(\eta \approx 1.0) = k^2(\eta = 0.9) \left[\frac{1.91}{1} \right] \quad (44)$$

All data presented in Figure 47 has been normalized as described above, and the predicted curves were calculated for $\eta = 1.0$. Due to the greater accuracy in the parameter extraction process, only control devices and devices with unweighted multilevel transducers with interleaved upper and lower electrodes were utilized to obtain the data shown in Figure 47.

Summary

The result of using component values found via the data extraction process described in Chapter 3 in the lumped transducer equivalent circuit model are predicted impedances and admittances which agree well with measured data for unapodized multilevel devices with thin (under 1000 Å) intermediate dielectric layers and interleaved upper and lower electrode fingers. For devices with thick dielectric layers, devices with solid upper electrodes, and apodized devices, this simple parameter extraction and equivalent circuit modeling process did not provide adequate correlation to observed device performance. While fundamental quantities extracted in this way may be useful, a

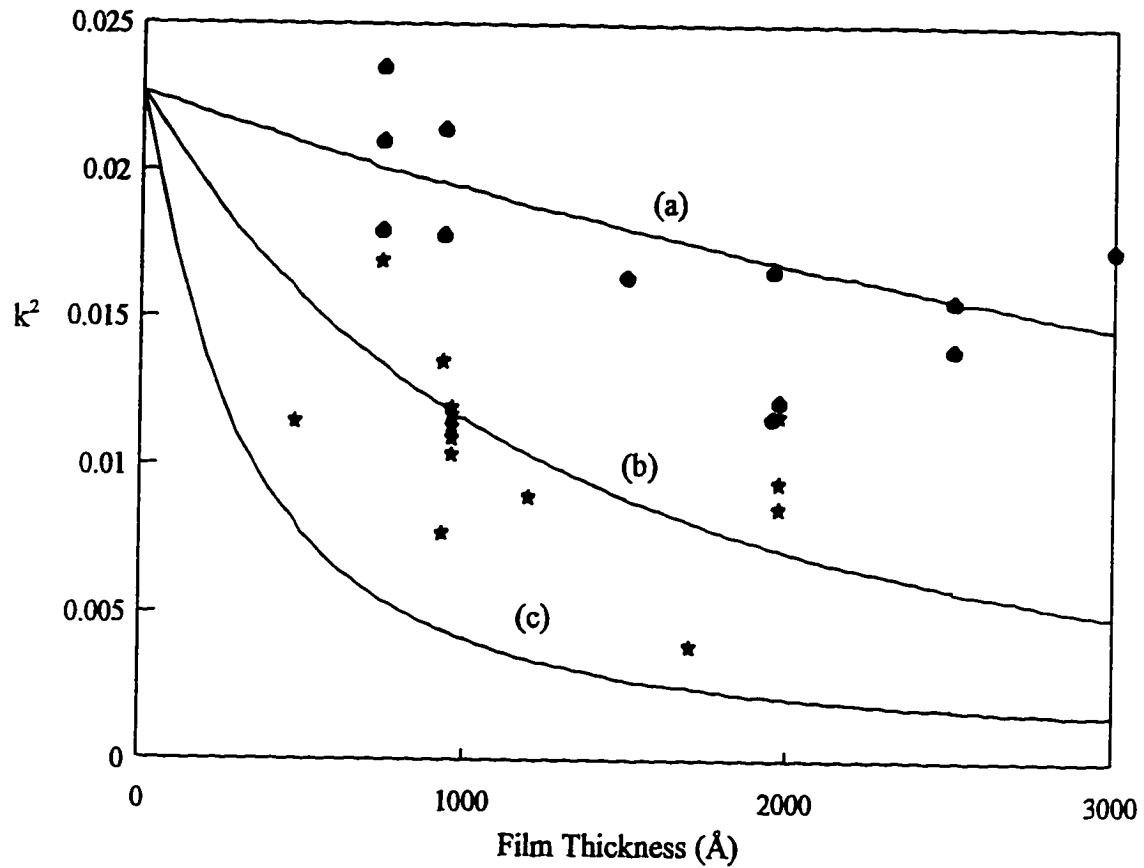


Figure 47. Electro-acoustic coupling factor k^2 as a function of Si_3N_4 film thickness for metallization ratio of 100%. Circles represent data from 100 MHz devices, stars represent data from 500 MHz devices. (a) Calculated coupling for 100 MHz devices, (b) Calculated coupling for 100 MHz devices, (c) Calculated coupling for 1.8 GHz devices.

more comprehensive transducer model such as the transmission line model presented in Chapter 6, which takes into account the specific transducer structure, must be utilized for accurate device analysis and performance prediction.

CHAPTER 6

TRANSMISSION LINE MODEL FOR SAW DEVICES

Background

SAW devices have been modeled in a variety of ways over the past few decades. The simplest model commonly used for SAW devices is the delta function model. While this model can not take into account circuit effects, harmonic operation, bulk wave interference or diffraction, it can be used to model the effects of electromagnetic feedthrough and triple-transit. A major limitation of the delta function model is that it cannot be used to predict absolute insertion loss levels. However, this model yields information on the relative insertion loss as a function of frequency for the transducer and device transfer functions, and is quite useful for a consideration of basic SAW design concepts. The delta function model approximates the electric field distribution between adjacent electrodes in an interdigital transducer (IDT) as a discrete number of delta function sources normal to the piezoelectric surface [7]. The time dependent electric field intensity will be proportional to the instantaneous charge accumulated on adjacent electrodes due to the time varying input voltage. For IDTs with adjacent electrodes attached to opposite polarity bus bars, the relative field polarities will alternate from electrode to electrode. Superposition implies that a summation of these impulse response sources, taking into account their relative phases with reference to a common (arbitrary)

position will yield the overall electric field intensity (and therefore the SAW potential and wave amplitude) excited by one IDT. The SAW IDT structure automatically performs the summation of a series of weighted, delayed versions of the input stimulus characteristic of a transversal filter [7, 8, 53]. The delta function model can be modified to predict harmonic responses and absolute insertion loss levels, and to predict fundamental responses more accurately, by introducing a frequency dependent element factor that takes into account the (one-dimensional) charge distribution under the electrodes.

Coupling-of-modes (COM) analysis, P-matrix analysis, and Transmission line/equivalent circuit analysis are all somewhat more comprehensive techniques used for modeling SAW device performance. These techniques are able to predict absolute insertion loss, along with predicting fundamental and harmonic operation. In their most basic forms, none of these models include bulk wave interactions or diffraction effects, although diffraction loss is easily included. With the proper handling, all three of these approaches can give equivalent results [7, 8, 67, 68].

Finally, lumped equivalent circuit models have occasionally been used to describe entire transducers using one simple equivalent circuit [69-71]. This technique is distinct from the transmission line equivalent circuit model described in the next section, which utilizes equivalent circuits to describe individual lines and gaps within the transducer and cascades these equivalent circuits to obtain the overall transducer response. While this approach does not describe device performance adequately in many cases, it is useful when extracting constants such as effective coupling from test structures. This approach was used in the equivalent parameter extraction procedure discussed in Chapter 3.

Transmission Line Model

One of the most versatile approaches for describing unique transducer structures is the transmission line equivalent circuit model [72]. As developed in this work, the transducers and reflective elements are viewed as being made up of individual elements which are either lines or gaps. The lines may represent either electrically connected metal taps within a transducer, or they may be metal or dielectric strips in a reflective element. The type of line will determine what type of discontinuity is presented to the traveling surface wave (electrical, mechanical, or both). The gaps represent the region of surface wave propagation between the aforementioned discontinuities. Sub-models are developed to find the 4x4 transmission matrix for each element, and the transmission matrices are cascaded together to yield the overall 4x4 transmission matrix for each transducer, reflector, or acoustic delay element in the device. Finally, these transmission matrices are converted into standard 2x2 form, and cascaded to yield the overall device transmission (ABCD) matrix. From this matrix, the device response can be calculated. The following sections detail the derivation of the lossless 4x4 transmission matrix for each type of line and gap, and present the conversion into 2x2 form based on loading for each. The relationship between the ABCD and S parameters commonly measured is also given for the case of arbitrary real source and load impedances.

Transmission Matrix of a Simple Lossless Gap

A simple lossless gap can be represented as a simple transmission line as shown in Figure 48(a). The transmission line characteristic impedance, Z , represents the acoustic impedance of the substrate and is given by

$$Z = Z_{a0} = \frac{k^2}{2\pi C_s v_0 W_a} \quad (41)$$

where k^2 is the substrate electromechanical coupling constant, C_s is the characteristic substrate capacitance per unit length, v_0 is the free surface SAW velocity, and W_a is the acoustic aperture, in wavelengths at the frequency of interest. The transmission angle θ_g is given by

$$\theta_g = \kappa l_{gap} \quad (42)$$

where the wavenumber κ is given by $\kappa = (2\pi/\lambda)$ and l_{gap} is the gap width in cm.

In terms of the propagation constant $\gamma = j\kappa$, the 2x2 transmission matrix relating v_1 and i_1 for the gap can be written [73]

$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z \sinh(\gamma l) \\ \frac{1}{Z} \sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \begin{bmatrix} v_2 \\ -i_2 \end{bmatrix} = T_d \begin{bmatrix} v_2 \\ -i_2 \end{bmatrix} \quad (43)$$

Modifying this circuit to yield the four port gap circuit shown in figure 48(b) results in a transmission matrix which is given by

$$\begin{bmatrix} v_1 \\ v_2 \\ i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & 0 & Z \sinh(\gamma l) & 0 \\ 0 & 1 & 0 & 0 \\ \frac{1}{Z} \sinh(\gamma l) & 0 & \cosh(\gamma l) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_3 \\ v_4 \\ -i_3 \\ -i_4 \end{bmatrix} = T_g \begin{bmatrix} v_3 \\ v_4 \\ -i_3 \\ -i_4 \end{bmatrix} \quad (44)$$

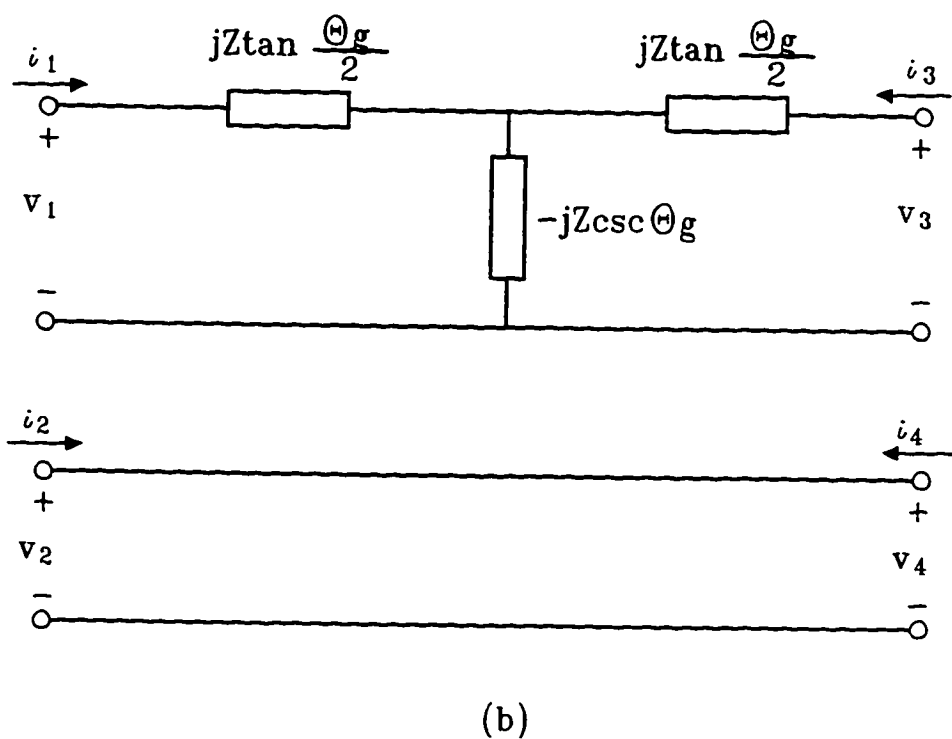
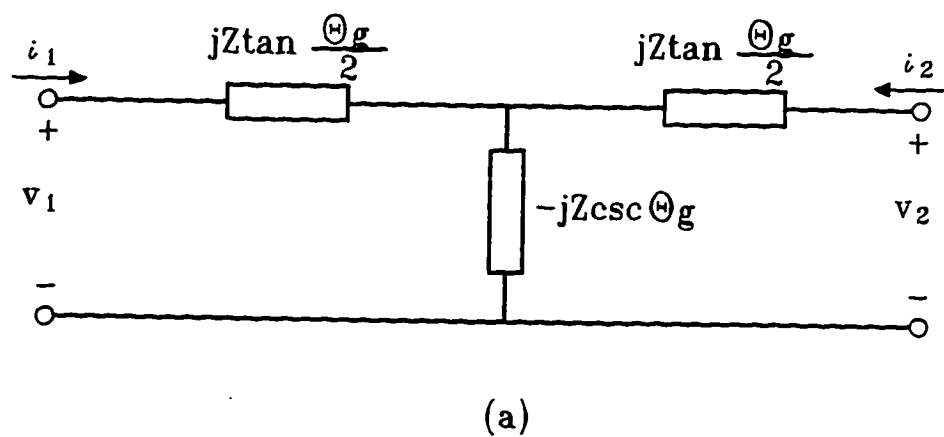


Figure 48. Transmission line model for a gap. (a) Two-port representation used for acoustic delays, (b) Four-port representation required for transducer analysis.

Transmission Matrix of a Lossless Metal Line

A metal line can be represented as a transmission line as shown in Figure 49. This model includes the effects of electromechanical coupling, electrostatic charge distribution, electrode capacitance, parasitic electrode resistance, and parasitic capacitance to ground, as well as effects which can lead to reflections internal to the transducers such as electrical shorting at the surface, mass loading, and energy storage. In Figure 49, components labeled by R_{p1} and R_{p2} represent the parasitic electrode resistances, and terms labeled C_{g1} and C_{g2} represent stray capacitances to ground. C_e is the electrode capacitance, calculated by [50, 51, 55, 72]

$$C_{en} = W_n \sqrt{\epsilon_o \epsilon_p^T} \frac{K(q_n)}{K(q'_n)} \quad (45)$$

where W_n represents the (active) acoustic aperture of electrode n , K is the complete Jacobian elliptic integral of the first kind [65], and q_n and q'_n are given by

$$q_n = \sin\left(\frac{\pi l_m}{2p}\right) \quad (50)$$

and

$$q'_n = \sqrt{1 - q^2} \quad , \quad (51)$$

where p is the transducer period (the center-to-center distance between adjacent unit cells within the transducer), ϵ_p^T is a dielectric constant characteristic of the substrate, and l_m is the width of the metal region, in cm.

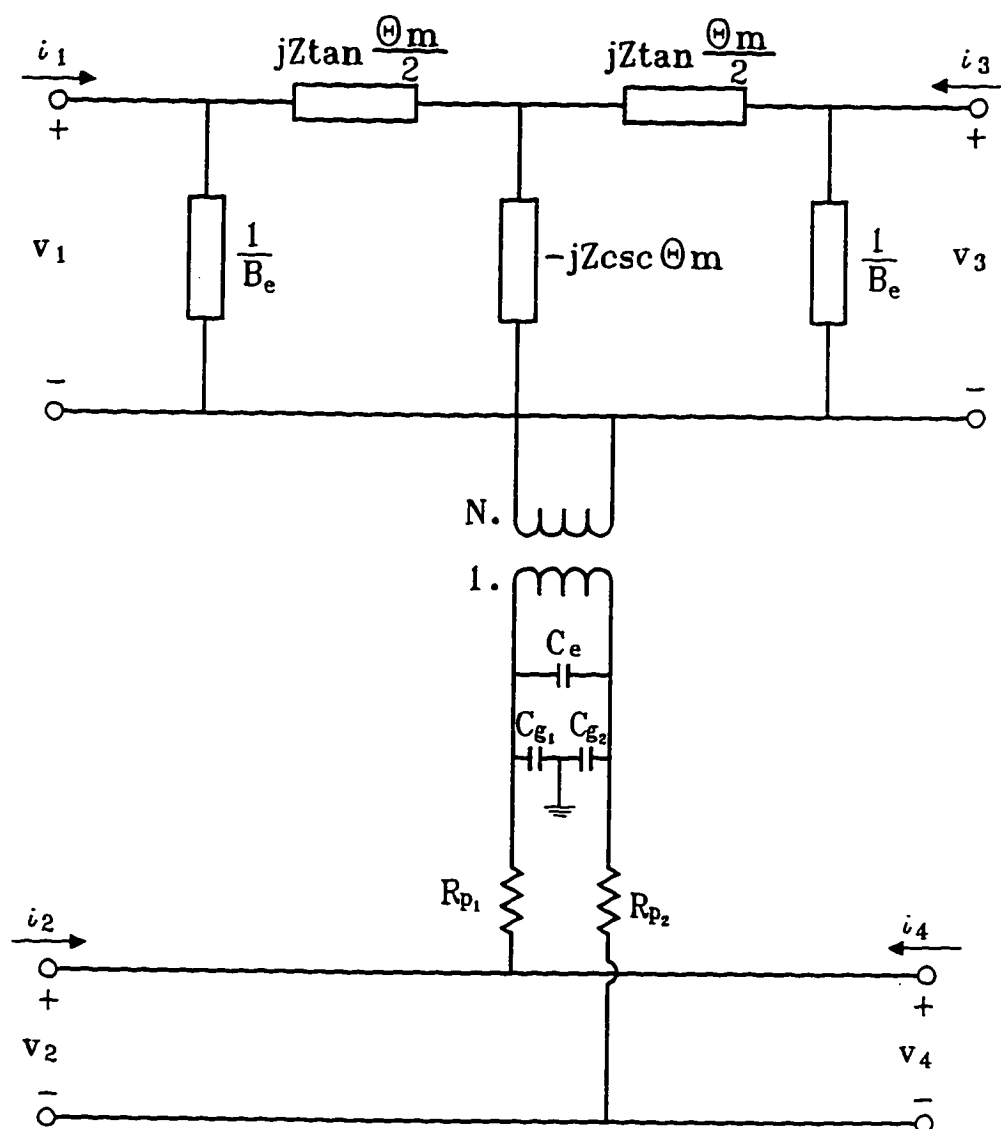


Figure 49. Transmission line model for a metal electrode.

The electromechanical coupling and the charge distribution (or element factor) are included in the transformer turns ratio, N . An approximate expression for N can be derived by calculating the input admittance of the electrical port of a unit cell consisting of a single electrode with a half gap on each side, terminated by the substrate characteristic impedance as shown in Figure 50, and equating the real part of the admittance (as a function of the turns ratio) with the acoustic conductance G_a . This calculation ignores the effects of energy storage and impedance differences between electrode and gap regions. Solving for the turns ratio yields the expression

$$N = \sqrt{2\pi f Z_{a0} (\epsilon_o + \epsilon_p^T) k^2 W} \left(\frac{1}{\sin\left(\frac{\theta_m}{2}\right)} \right) \left| \frac{\sin(\pi s) P_m(\cos(\Delta))}{P_{-s}(-\cos(\Delta))} \right|, \quad (52)$$

where θ_m represents the transmission angle under the metal line, given by

$$\theta_m = \kappa l_m, \quad (53)$$

f is the calculation frequency, W is the acoustic aperture, k^2 is the acousto-electric coupling, s is a factor which depends on the number of electrodes per wavelength and the harmonic at which the device is operating [55] which, for non-split fingers at the fundamental frequency is $s = 1/2$, m is an integer given by

$$m \leq \frac{\kappa p}{2\pi} \leq m + 1 \quad (54)$$

and Δ is given by

$$\Delta = \pi \eta. \quad (55)$$

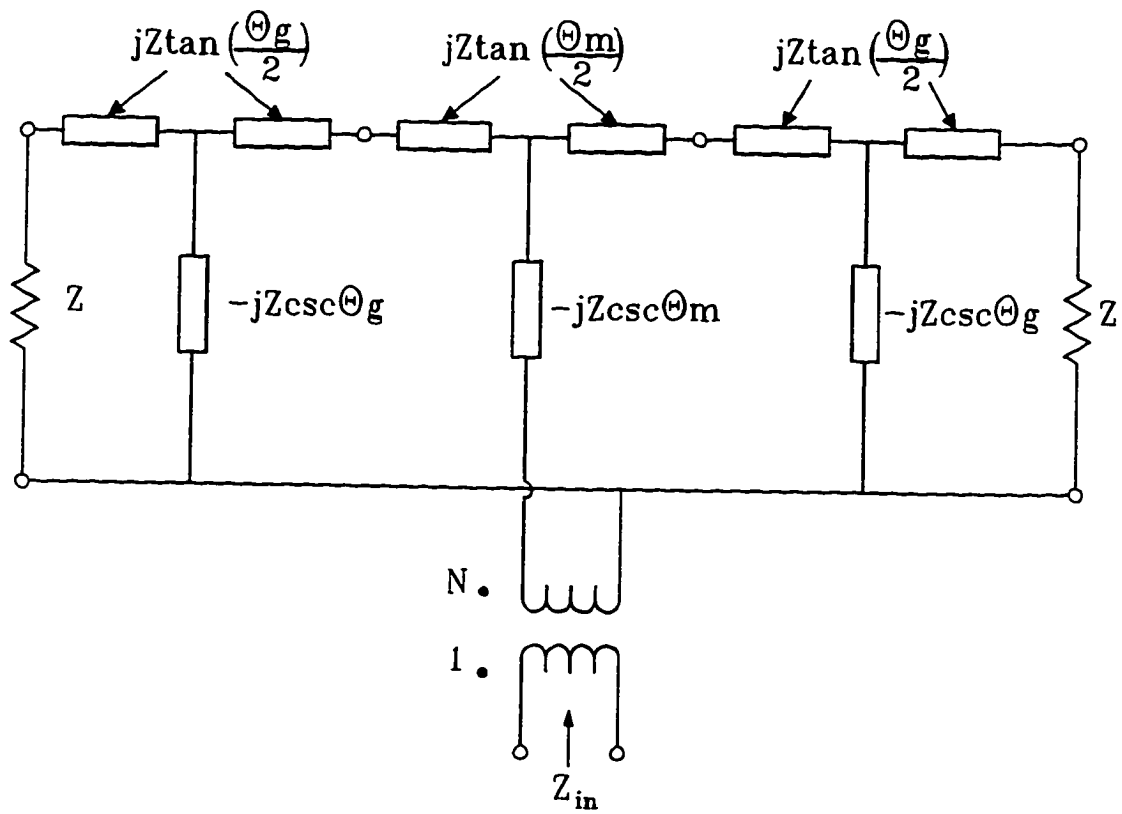


Figure 50. Transmission line model for a unit cell used in calculating the electrode turns ratio.

Electrical shorting and mass loading effects are taken into account by varying the characteristic impedance of the transmission line segment. The impedance of a conductive strip is calculated as before, using a velocity modified to reflect the effect of shorting,

$$Z_s = \frac{k^2}{2\pi C_s v_m W} \quad (56)$$

where v_m is the velocity in the metallized region due to shorting, approximated by [53,55]

$$v_m \approx v_0 \left(1 - \frac{k^2}{2} \right) . \quad (57)$$

Li calculates the impedance discontinuity caused by a simple step on YZ LiNbO₃, ignoring any effects of electrical shorting, as [63]

$$Z_{step} = Z_{charac} \left(\frac{1+\Gamma}{1-\Gamma} \right) \quad (58)$$

where

$$\Gamma = 0.33 \left(\frac{h}{\lambda} \right) \quad (59)$$

for this substrate. Because the multilevel transducer may have both the shorting and the mechanical reflection mechanisms generating reflections at metal electrodes, and the mechanical effects only for gaps between electrodes, different transmission line impedances are used for these two regions. In both cases, equation (58) is used, with the characteristic impedance Z_{charac} equal to the substrate acoustic impedance given by equation (45) for the gaps, and equal to the shorted impedance Z_s given by equation (56) for the metal electrode regions.

Energy storage effects are represented in the transmission line model by a shunt susceptance, B_e . This is calculated by [68, 74]

$$B_e = 42 \left(\frac{h}{\lambda} \right)^2 Y_0 \quad (60)$$

where h is the step thickness and λ is the wavelength at the frequency of interest. Y_0 is the substrate characteristic admittance,

$$Y_0 = \frac{1}{Z_{a0}} \quad (61)$$

Using these parameters, the 4x4 transmission matrix of the single electrode shown in Figure 49 can be written

$$\begin{bmatrix} v_1^i \\ v_2^i \\ i_1^i \\ i_2^i \end{bmatrix} = \begin{bmatrix} T_{11}^i & T_{12}^i & T_{13}^i & T_{14}^i \\ T_{21}^i & T_{22}^i & T_{23}^i & T_{24}^i \\ T_{31}^i & T_{32}^i & T_{33}^i & T_{34}^i \\ T_{41}^i & T_{42}^i & T_{43}^i & T_{44}^i \end{bmatrix} \begin{bmatrix} v_3^i \\ v_4^i \\ -i_3^i \\ -i_4^i \end{bmatrix} \quad (62)$$

where the superscript denotes the i^{th} electrode in a transducer. The components in the matrix of equation (59) are given by the following set of relationships

$$T_{11}^i = \frac{1}{K'} \left[L \left(AB_e (H - 2N_i^2 C) - N_i^2 C + B - A \right) + CM (AB_e H + B - A) \right] \quad (63)$$

$$T_{12}^i = T_{43}^i = \frac{[AN_i L]}{K'} \quad (64)$$

$$T_{13}^i = \frac{1}{K'} \left[A \left(L (H - 2N_i^2 C) + HCM \right) \right] \quad (65)$$

$$T'_{31} = \frac{1+AB_e}{K'} \left[L(B_e H - 2N_i^2 C B_e - 1) - CM(1 - B_e H) \right] \quad (66)$$

$$T'_{32} = T'_{41} = \frac{N_i L(1+AB_e)}{K'} \quad (67)$$

$$T'_{33} = \frac{1}{K'} \left[L(B - A - N_i^2 C + AB_e(H - 2N_i^2 C)) + CM(B - A + AHB_e) \right] \quad (68)$$

$$T'_{42} = \frac{BM - N_i^2 L}{K'} \quad (69)$$

$$T'_{14} = T'_{21} = T'_{23} = T'_{24} = T'_{34} = 0 \quad (70)$$

$$T'_{22} = T'_{44} = 1 \quad (71)$$

where A, B, C, D, E, F, G, H, K', L, and M are defined by

$$A = jZ \tan\left(\frac{\theta_m}{2}\right) \quad (72)$$

$$B = jZ \csc(\theta_m) \quad (73)$$

$$C = R_{p1} + R_{p2} \quad (74)$$

$$D = \frac{1}{j\omega C_{g1}} \quad (75)$$

$$E = \frac{1}{j\omega C_{g2}} \quad (76)$$

$$F = j\omega C_e \quad (77)$$

$$G = \frac{B}{A} = \frac{1}{2} \csc^2\left(\frac{\theta_m}{2}\right) \quad (78)$$

$$H = 2B - A = jZ \cot\left(\frac{\theta_m}{2}\right) \quad (79)$$

$$K' = (D + E)(B - N_i^2 C) + BC(1 + F + FD) \quad (80)$$

$$L = D + E \quad (81)$$

and

$$M = 1 + F + FD \quad (82)$$

In equations (63) through (82), θ_m represents the transmission angle under the metal line, and N_i is the turns ratio for the electrode in question.

Transmission Matrix of a Transducer

The overall 4x4 transmission matrix of a transducer, as illustrated by Figure 51, can now be found by cascading the transmission matrices for each line and gap. For a transducer with n lines, the overall T matrix can be written

$$T = T_l^1 \times T_g \times T_l^2 \times T_g \times \dots \times T_l^{n-1} \times T_g \times T_l^n \quad (83)$$

where the line and gap transmission matrices are given by equations (62) and (48) respectively.

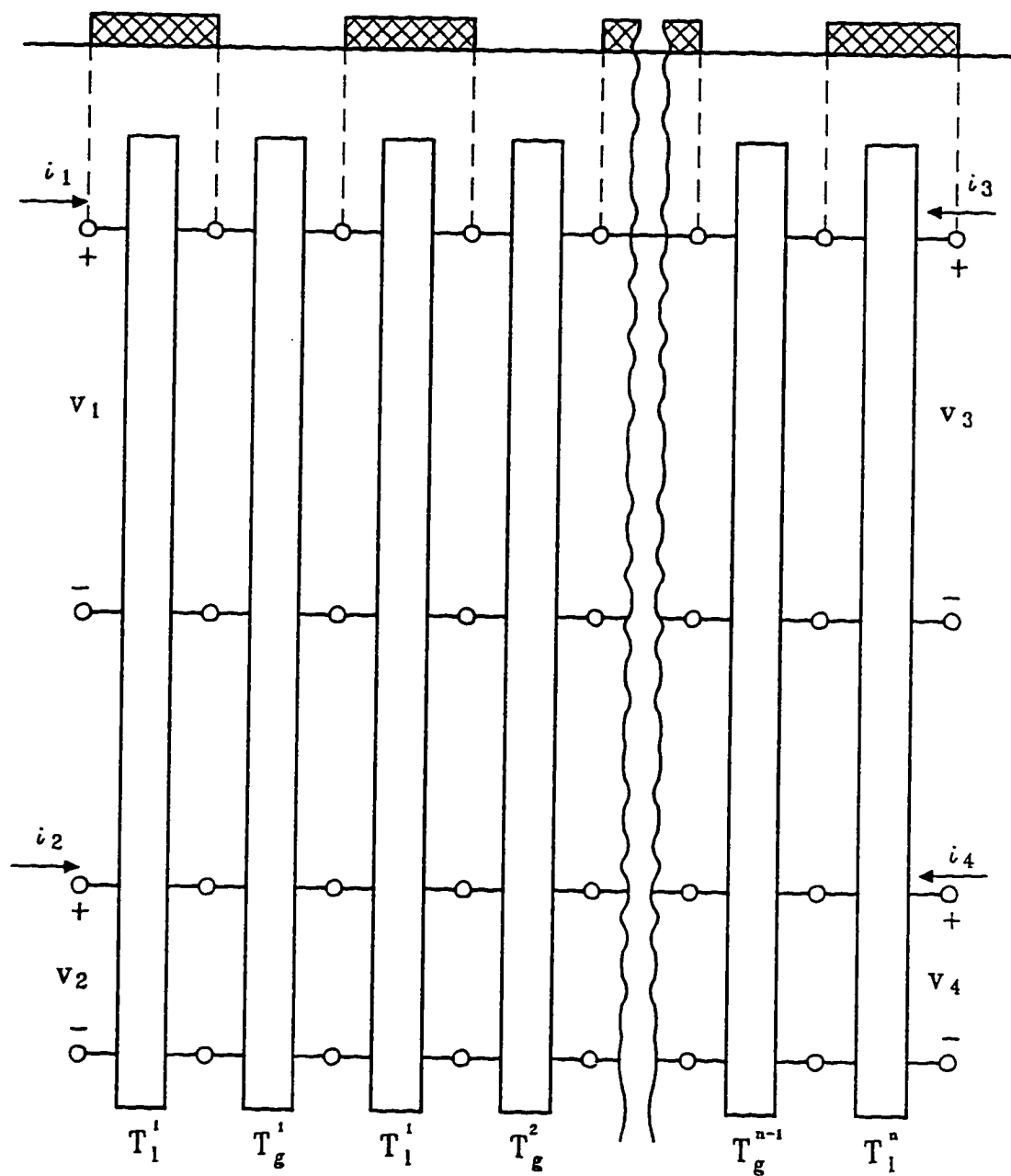


Figure 51. Transmission matrix of a transducer. The 4x4 transmission matrix for the transducer is calculated by cascading T matrices for lines and gaps.

Transmission Matrix of a Two-Transducer Device

A simple two-transducer device can be modeled by cascading the transmission matrices of the input transducer, the transducer inner edge-to-edge acoustic delay, and the output transducer, as shown in Figure 52. Considering the overall device, the acoustic delay line that represents the edge-to-edge separation of the transducers can be described by a simple acoustic gap. In order to describe the device properly, it is clear that a 2x2 transmission matrix must be used for the acoustic delay, since there is no direct electrical short between input and output electrical ports (as is the case for the 4x4 used for the acoustic gaps within the transducer). Thus, in order to cascade the transducer transmission matrices with the 2x2 matrix for the acoustic delay, the transducer 4x4 matrices must first be converted into 2x2 form, using the appropriate port terminations.

For the input transducer, the signal undergoes an electrical to acoustic conversion, so we want the transmission matrix from the input electrical port to the output acoustic port. Thus, the input acoustic port is terminated in the substrate characteristic impedance, and the output electrical port is open circuited, as shown in Figure 53 (a). Assuming T_{11} through T_{44} are the components of the transducer 4x4 transmission matrix, and Z is the characteristic acoustic impedance, the conversion to 2x2 can be done using

$$A'' = -\left(\frac{T_{11} + T_{31}Z}{T_{12} + T_{32}Z}\right) \quad (84)$$

$$B'' = -\left(\frac{T_{13} + T_{33}Z}{T_{12} + T_{32}Z}\right) \quad (85)$$

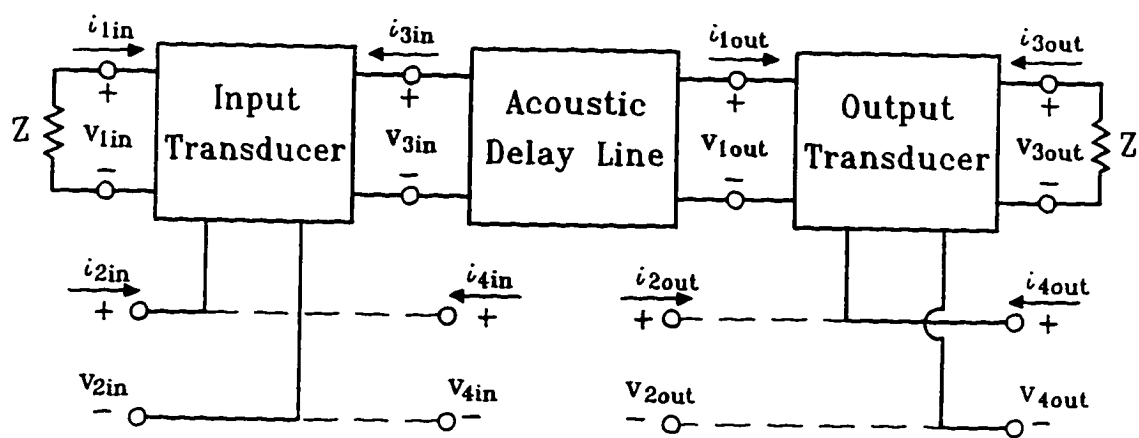
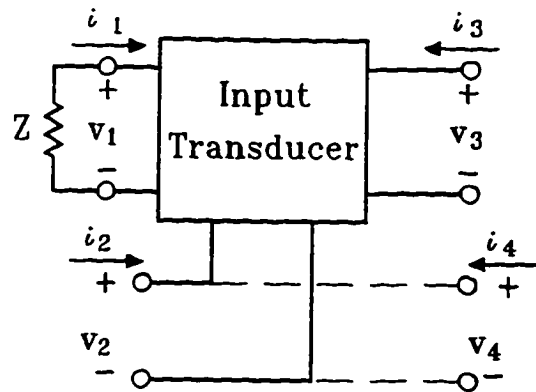
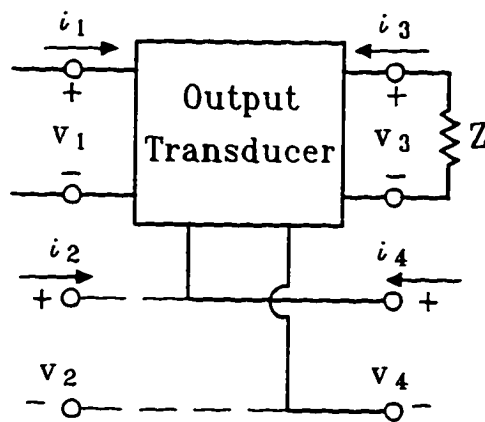


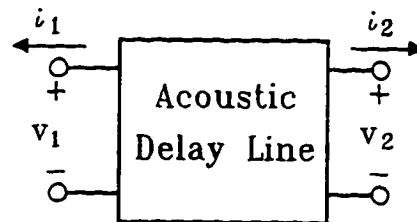
Figure 52. Transmission line model of a two transducer device. Device transmission matrix obtained by cascading transducer and acoustic delay T matrices.



(a)



(b)



(c)

Figure 53. Four-port to two-port transmission line model conversion. (a) Input transducer electric to acoustic conversion, (b) Output transducer acoustic to electric conversion, (c) Acoustic delay two-port transmission line.

$$C'' = T_{41} - T_{42} \left(\frac{T_{11} + T_{31}Z}{T_{12} + T_{32}Z} \right) \quad (86)$$

$$D'' = T_{43} - T_{42} \left(\frac{T_{13} + T_{33}Z}{T_{12} + T_{32}Z} \right) \quad (87)$$

So we have the relationship

$$\begin{bmatrix} v_2 \\ i_2 \end{bmatrix} = \begin{bmatrix} A'' & B'' \\ C'' & D'' \end{bmatrix} \begin{bmatrix} v_3 \\ -i_3 \end{bmatrix} \quad (88)$$

For the output transducer, the signal undergoes an acoustic to electrical conversion, so we want the transmission matrix from the input acoustic port to the output electrical port. Thus, the input electrical port is open circuited, and the output acoustic port is terminated in the substrate characteristic impedance, as shown in Figure 53 (b).

Now, using the fact that for an arbitrary 2-port network for which reciprocity holds

$$AD - BC = \|T\| = 1 \quad , \quad (89)$$

it can be shown that the 2x2 transmission matrix for the acoustic to electric conversion is simply the 2x2 matrix for the electric to acoustic conversion with the diagonal terms reversed, or

$$\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = \begin{bmatrix} D'' & B'' \\ C'' & A'' \end{bmatrix} \quad (90)$$

Thus, equations (62) through (83) can be used to calculate the electric to acoustic transmission matrix for the output transducer, and then equation (90) can be used to obtain the acoustic to electric transmission matrix, which yields the relationship

$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{bmatrix} v_4 \\ -i_4 \end{bmatrix} \quad (91)$$

The transmission matrix for the acoustic delay is given by equation (47), which considering Figure 53 (c) yields the relationship

$$\begin{bmatrix} v_1 \\ i_1 \end{bmatrix} = T_d \begin{bmatrix} v_2 \\ -i_2 \end{bmatrix} \quad (92)$$

Cascading the transmission matrices for all three components yields the overall device relationship between the input and output electrical parameters

$$\begin{bmatrix} v_2 \\ i_2 \end{bmatrix} = T \begin{bmatrix} v_4 \\ -i_4 \end{bmatrix} \quad (93)$$

where the transmission matrix for the entire device is given by

$$T = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A'' & B'' \\ C'' & D'' \end{bmatrix} T_d \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \quad (94)$$

Overall Device Response

The S-parameters for the overall device response can be found from the transmission matrix, for arbitrary real source and load impedances Z_{os} and Z_{ol} using

$$S_{11} = S_{22} = \frac{A + \left(\frac{1}{Z_{0L}}\right)B - Z_{0S}C - D\left(\frac{Z_{0S}}{Z_{0L}}\right)}{A + \left(\frac{1}{Z_{0L}}\right)B + Z_{0S}C + D\left(\frac{Z_{0S}}{Z_{0L}}\right)} \quad (95)$$

$$S_{12} = S_{21} = \frac{2(AD - BC)}{\left(\frac{Z_{0L}}{Z_{0S}}\right)A + \left(\frac{1}{Z_{0S}}\right)B + Z_{0L}C + D} \quad (96)$$

Propagation Loss

Strictly speaking, propagation loss should be included in a transmission line model by allowing the propagation constant, γ , to be complex. For lossless transmission lines, γ is pure imaginary [73]. Introducing a real part to γ introduces an attenuation to the wave as it propagates. Since all of the transducers used in this work are relatively short, a simpler approximation has been made to include propagation loss in the current model. As described by Morgan [55], propagation loss is frequency dependent, and for YZ LiNbO₃ can be written

$$\alpha \approx \left(0.544725 f + 2.52294 f^{1.9}\right) \quad (97)$$

where f is the frequency in GHz, and α is the propagation loss given in dB/cm. A velocity of 3488 m/sec was used to arrive at the constants given in equation (97). In the current model, this expression is used to calculate an additive loss term due to propagation over the free surface path between the two transducers. No attempt is made to take propagation loss into account in the transducer regions.

Summary

The transmission line model developed in the current work is a model which cascades the transmission matrices for individual lines and gaps to obtain the transducer or reflector transmission matrices, and then cascades transducer and acoustic delay transmission matrices to obtain the transmission matrix for the overall device response. As such, it is fairly time consuming to run, taking several minutes on a 75 MHz 486 PC to evaluate the response of a device with two unweighted transducers, each consisting of twenty electrodes. While the flexibility of this model allow the user to individually vary the properties of each line and gap arbitrarily, efficient application to periodic transducer structures may require some modification to reduce computation time.

CHAPTER 7

EXPERIMENTAL RESULTS AND COMPARISON WITH TRANSMISSION LINE MODEL

Introduction

Conventional single-level split finger 50 MHz control devices and 100 MHz and 500 MHz multilevel transducer devices and test structures fabricated on YZ LiNbO₃ were discussed in Chapter 5. Parameter extraction was performed on typical devices of each type. Extracted transducer equivalent circuit parameters presented in Chapter 5 were used in the transmission line model discussed in Chapter 6, resulting in simulations which predict device performance fairly well as shown in the remainder of this chapter. Additional delay lines using multilevel transducer technology were fabricated with a nominal fundamental operating frequency of 1.8 GHz. The electrode width for these transducers was 0.95 μm , and five different intermediate nitride layer thicknesses ranging from 360 Å to 1440 Å were used.

Transmission Line Model of Control Devices

The unmatched response of a typical 50 MHz control device fabricated using single level unweighted split finger transducers was shown in Figure 28. Transmission line

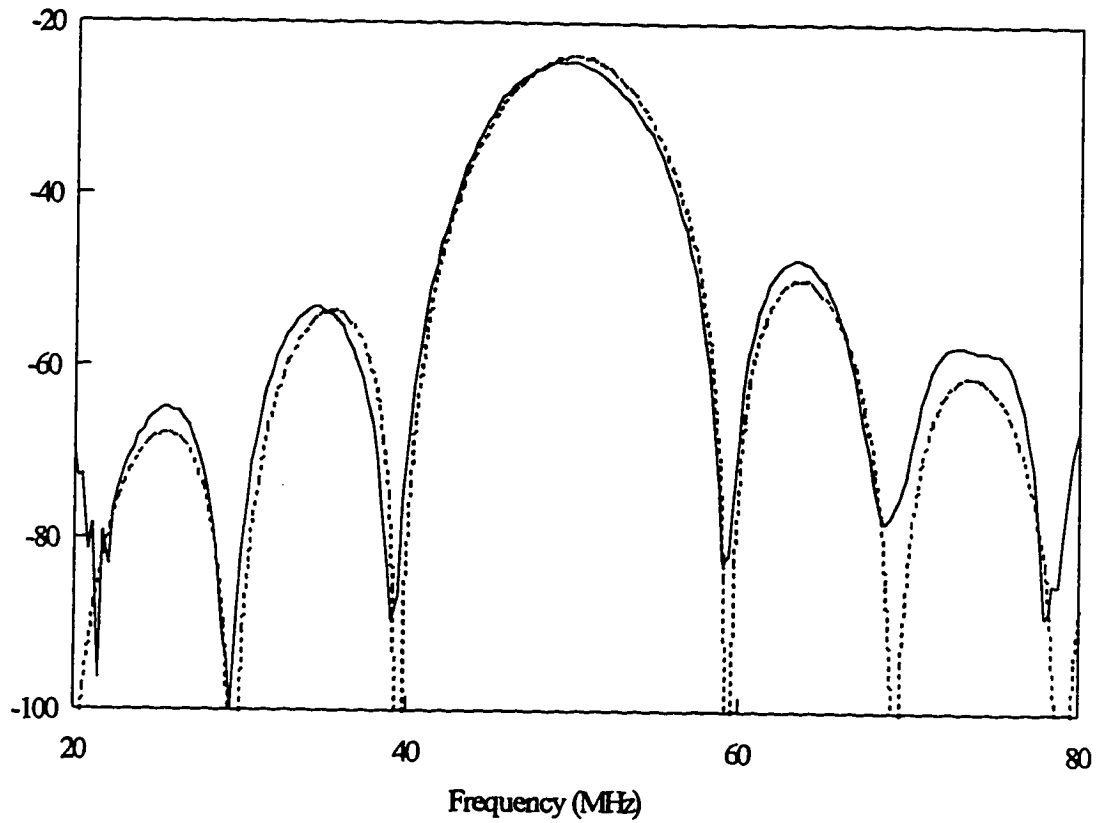


Figure 54. Transmission line model of 50 MHz control device.

modeling of this device yields the simulation shown in Figure 54. The equivalent circuit parameters R_t , C_t^{eff} , and k^2 which were extracted in Chapter 5 were used in this model. Since the actual device had multiple electrodes electrically in parallel, and the transmission line model treats the parasitic resistance of each electrode separately as two resistances in parallel, it was necessary to calculate the electrode parasitic resistance from the extracted transducer parasitic resistance using

$$R_p = 2NR_t \quad (98)$$

where N represents the total number of electrode taps [53].

Transmission Line Model of Multilevel Devices

100 MHz Multilevel Devices

The unmatched response of a 100 MHz multilevel device with interleaved upper and lower electrode patterns was shown in Figure 29. Figure 55 illustrates the reasonably good simulation of this device provided by transmission line modeling. Once again, the transducer parasitic resistance extracted in Chapter 5 has been modified as described by equation (95) to yield the appropriate values for the electrode parasitic resistance R_p in the transmission line model. For all multilevel transducers modeled, the actual extracted values of C_s^{eff} and k^2 were utilized in the transmission line model, not the compensated 100% metallization values presented in Chapter 5. This was necessary to achieve accurate device simulation because the metallization ratios varied from device to device, and the transmission line model developed here assumes that extracted parameters which take into account the actual device geometry, including such variations, will be used. For predictive purposes, the effective 100% metallization ratio values presented in Chapter 5 can be converted to equivalent values of any actual device metallization ratio using equations (34) and (39). Alternatively, a transmission line model could be developed which incorporates theoretical variations in k^2 and C_s^{eff} with metallization ratio into the model equations, as in [75]. Applying such an approach to multilevel transducers, however, would require a-priori knowledge of the dependence of these parameters on nitride film thickness and material properties. Thus, this approach was not considered further for the current work.

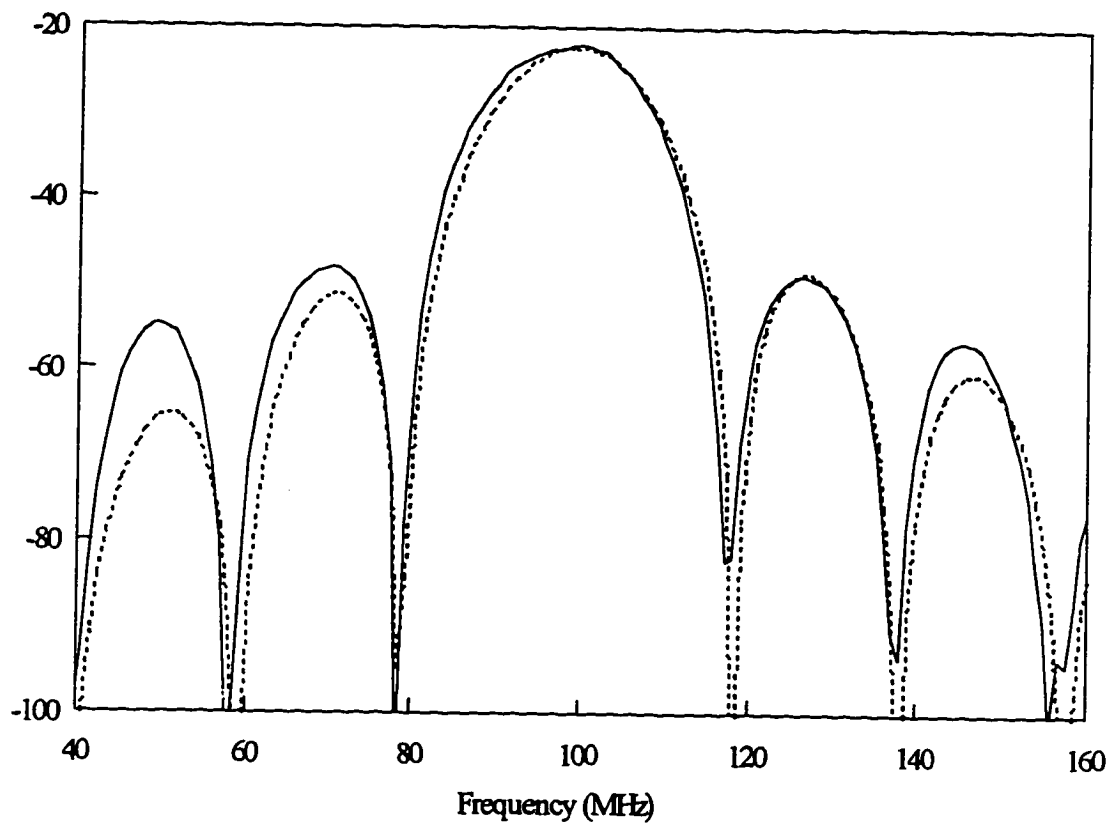


Figure 55. Transmission line model of a 100 MHz device using multilevel transducers with interleaved upper and lower electrodes.

500 MHz Multilevel Devices

The unmatched response of a 500 MHz multilevel device with interleaved upper and lower electrode patterns was shown in Figure 38. Figure 56 illustrates the relatively accurate simulation of a similar multilevel device using the transmission line model. Once again, the transducer parasitic resistance extracted in Chapter 5 has been modified as described by equation (98) to yield the appropriate values for the electrode parasitic

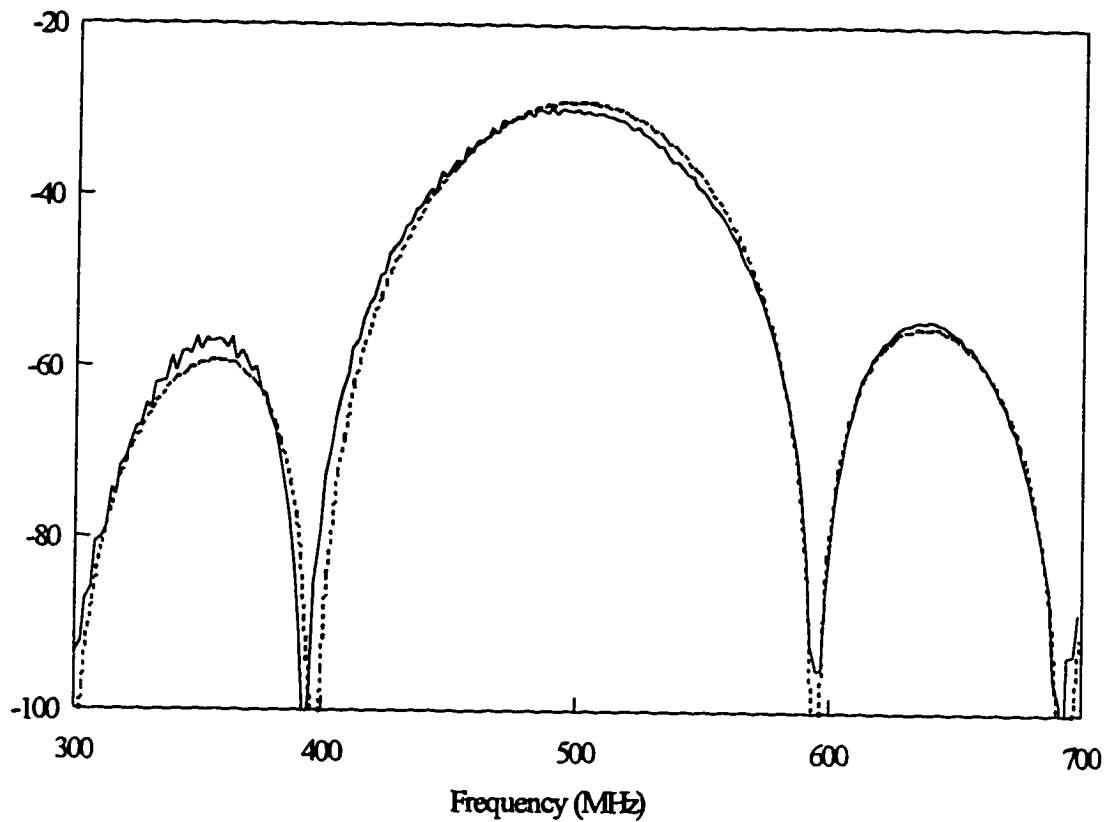


Figure 56. Transmission line model of a 500 MHz device using multilevel transducers with interleaved upper and lower electrodes.

resistance R_p in the transmission line model, and the actual extracted values of C_p^{eff} and k^2 were utilized in the transmission line model.

1.8 GHz Devices

Delay lines and other test structures using multilevel transducer technology were fabricated with a nominal fundamental operating frequency of 1.8 GHz. Electrode widths for these transducers was $0.95\ \mu\text{m}$, and five different intermediate nitride layer thicknesses

ranging from 360 Å to 1440 Å were used. Because of the high fundamental operating frequency, components such as bond pads and bond wires provide substantial capacitive and inductive reactances. If the transducers are properly designed, these reactances can be used to effectively match the devices to 50 Ω, alleviating the need for discrete matching components. To this end, and because devices fabricated with the five different nitride thicknesses were likely to have different impedance characteristics, three transducer apertures were used: 80 λ, 40 λ, and 20 λ. The transducers all had 63 electrode pairs.

Figure 57 shows the frequency response of a 1.8 GHz delay line fabricated using multilevel transducer technology with interleaved upper and lower electrodes. This delay line consists of two unweighted transducers, each with 63 electrodes, and has an aperture of 20 λ. Once again, the multilevel transducer device demonstrates the $[\sin(x)/x]^2$ frequency response characteristic of a device with unweighted transducers. Ripples in the experimental response are the result of a third, ungrounded transducer in the propagation path between the input and output transducers generating signals which reach the output transducer before and after the desired signal.

Parameter extraction did not work well for the 1.8 GHz devices, principally because it was not possible to construct accurate calibration standards using the package and fixture available. While the S_{12} data will be accurate to within a fraction of a dB with a simple through calibration, performing parameter extraction relies on having accurate S_{11} and S_{22} data. Although standards were built in duplicates of the surface mount packages used for the 1.8 GHz SAW devices, we were unable to obtain high precision standards, particularly the open. Because parameter extraction could not be performed on these

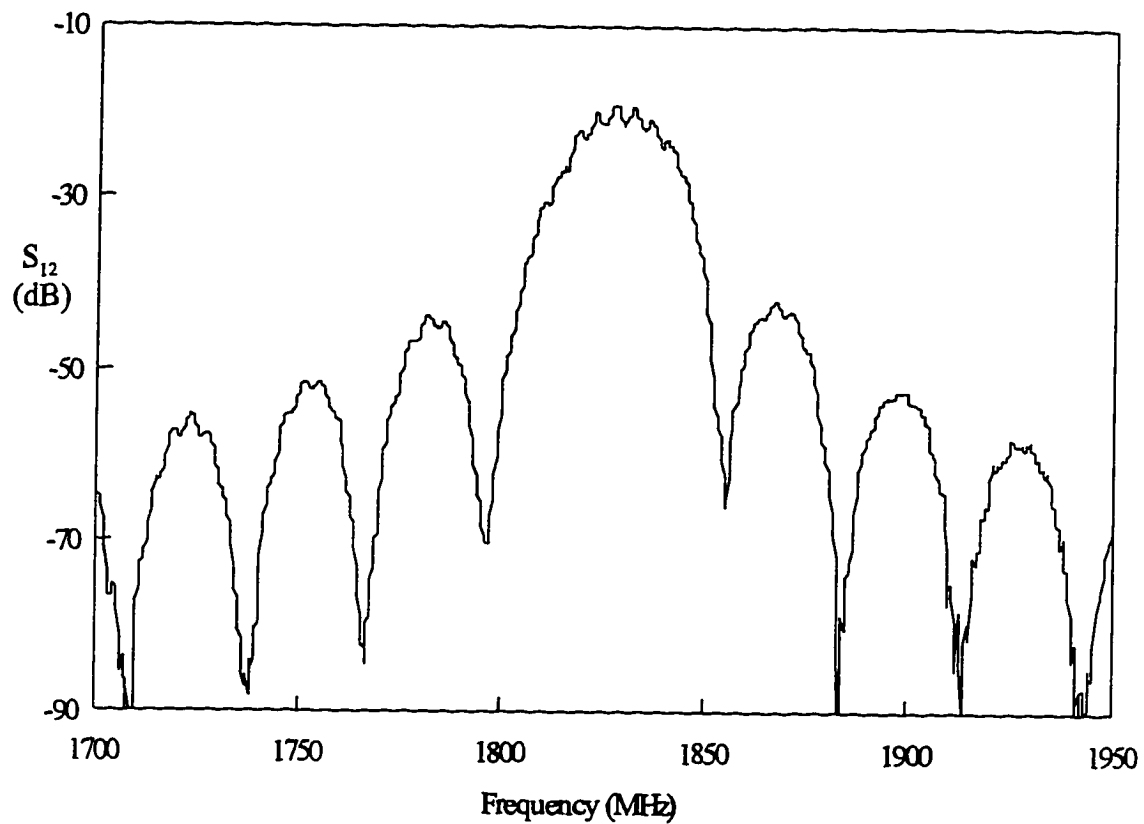


Figure 57. Frequency response of a 1.8 GHz device using multilevel transducers with interleaved upper and lower electrodes.

devices, the data for coupling as a function of dielectric layer thickness and frequency was extended to 1.8 GHz as shown in Chapter 5, and a value for coupling of $k^2 = 0.0043$ was estimated.

The value approximated for k^2 and the value $C_s^{\text{eff}} = 11.811$ pF/cm extracted and presented in Chapter 5 were substituted into the transmission line model. As shown in Figure 58, the transmission line model predicts the response of this delay line fairly well. B_c was set to zero to avoid substantial distortion of the model response. Based on

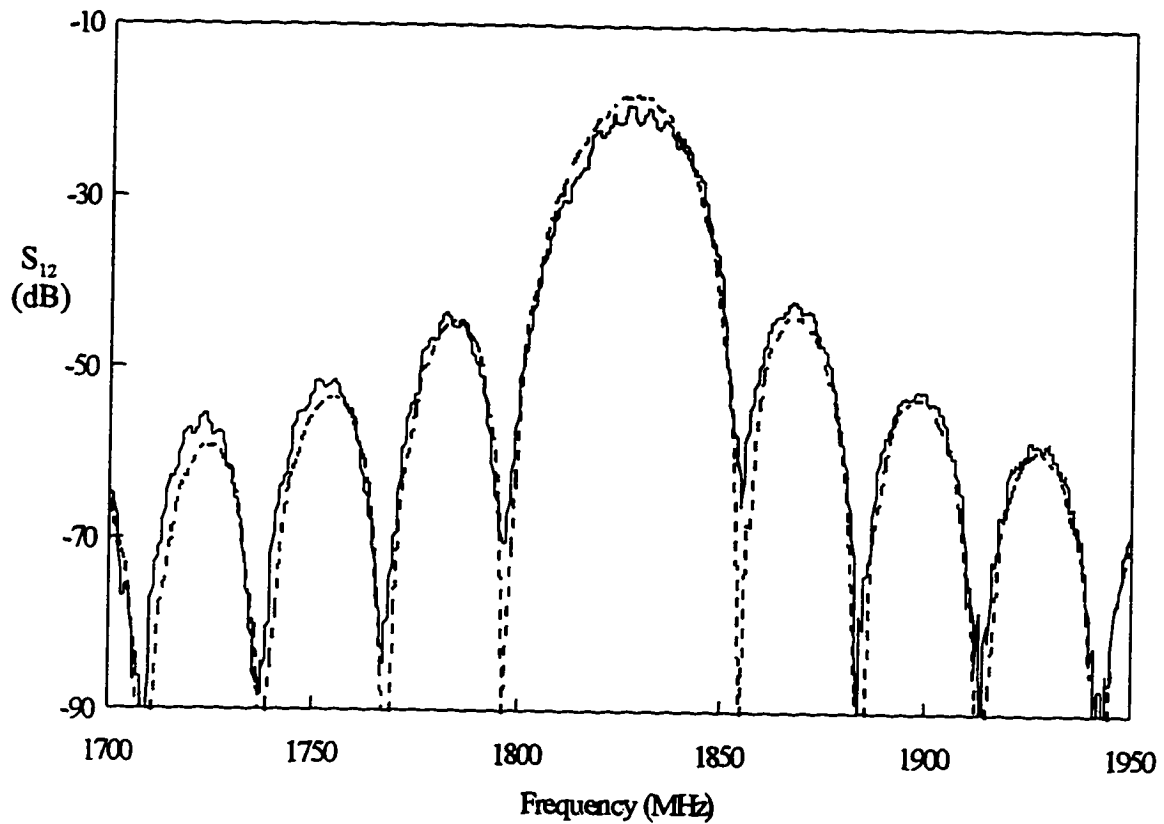


Figure 58. Transmission line model of a 1.8 GHz device using multilevel transducers with interleaved upper and lower electrodes. Solid line is experimental frequency response, dashed line is model prediction.

preliminary trial runs, it became clear that the equation used for B_e , equation (60), only applies for frequencies well below 1.8 GHz. Based on the number of taps in the 1.8 GHz transducers and the extracted resistance and number of taps in the 500 MHz transducers, an approximate value of $R_{p1} = R_{p2} = 230 \Omega$ was used.

Summary

The transmission line model described in Chapter 6 was used to model SAW devices consisting of both conventional single level transducers and multilevel transducers. The multilevel transducers modeled ranged in frequency from 100 MHz to 1.8 GHz. Good correlation was obtained between experimental data and model predictions for all devices evaluated. Accurate prediction of the 1.8 GHz device response in the absence of directly extracted equivalent circuit parameters served to verify the extensibility of the simple capacitive model for variation in coupling with dielectric layer thickness presented previously.

CHAPTER 8

HIGH FREQUENCY LOW-LOSS DEVICES

Low-Loss Transducer Structures and Device Configurations

Several low-loss transducer and device configurations have been developed over the past two decades, including the interdigitated interdigital transducer (IIDT), SAW resonators and resonator filters, ladder-type resonator filters, and transversely coupled resonator filters. One of the most widely used low-loss transducer structures is the unidirectional transducer, or UDT. Unidirectional transducers launch acoustic energy in only one direction, avoiding the automatic 3 dB per transducer loss associated with the bidirectional nature of conventional SAW transducers. UDTs can be created in a number of ways, including the three phase UDT, the single phase UDT (SPUDT), the floating electrode UDT (FEUDT), and the group type UDT (GUDT).

SPUDT and FEUDT transducers utilize the ability to separately control the transduction and reflection processes within a transducer. The transducers are designed such that the center of transduction and the center of reflection are spatially offset by the appropriate amount to cause the transduction and reflection to add in phase in one propagation direction, and to add out of phase and cancel in the opposite direction, thus effectively launching a wave from the transducer in only one direction.

GUDT and multiphase UDTs utilize acoustic offsets and external circuit phasing to create structures which launch waves in only one direction as well. Three phase UDTs consist of three lines and spaces per wavelength, with each line connected to one of the three bus bars. These bus bars are driven 120° apart, resulting in acoustic waves which add in one direction and cancel in the other. This arrangement requires the use of insulating crossovers in conventional manufacturing practice, complicating the fabrication of these devices. The GUDT in its simplest form is much more straightforward, consisting of two sections which are acoustically offset by an odd multiple of 90° at device center frequency, and which are driven electrically 90° out of phase [18], as shown in Figure 59. The end result is once again a wave launched in only one direction.

Potential for Low-Loss Application of Multilevel Transducers

As shown in Chapter 6, preliminary 100 MHz multilevel devices demonstrated in this work all showed unmatched insertion losses in excess of 20 dB in a 50 ohm system. While losses on this order of magnitude are to be expected for this device structure based on preliminary equivalent circuit modeling, the current trend in high frequency systems is to require losses below 10-12 dB. This is particularly true of devices for the growing mobile communication industry. Thus it will be necessary to develop techniques to reduce the insertion loss on devices fabricated using this transducer structure.

For many of the multilevel devices tested, the dominant source of loss was electrical mismatch. Thus, by providing a conjugate match from the device to the electrical system on each port, the device losses can be reduced substantially. Matching of

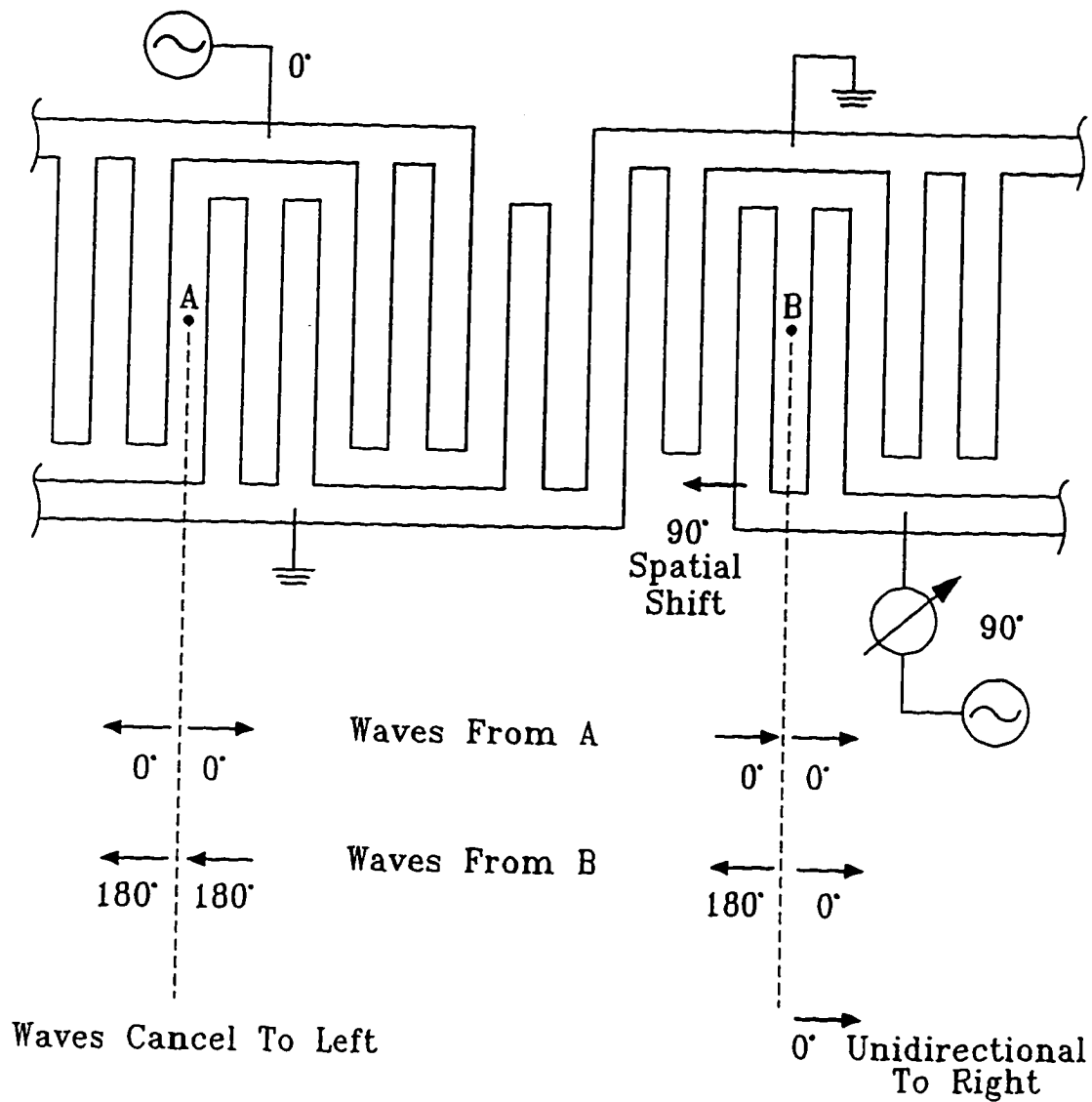


Figure 59. Simple group-type unidirectional transducer structure and operating principle.

Waves launched bi-directionally from points A and B add in phase to the right and cancel to the left with external phasing shown.

the bi-directional transducer multilevel devices which had unmatched insertion losses of approximately 30 dB produced, in some cases, losses of below 10 dB, as discussed in Chapter 8. This demonstrates that the multilevel transducer structure is not inherently lossy, and has the capability of operating with low loss. However, matching of any bi-directional transducer device introduces some undesirable effects such as enhancement of the triple-transit signal. Because this is not acceptable in a number of applications, it is desirable to demonstrate that multilevel transducers can be used for other low-loss device configurations as well, which can be tailored to avoid undesirable triple transit characteristics.

Any device configuration commonly used to achieve low-loss performance, such as the GUDT, IIDT, and others discussed above can potentially be implemented using this type of transducer. In order to demonstrate low-loss performance in the current work, a simple low-loss test structure was desired. Lack of a priori information about impedance characteristics of the multilevel transducer and the lack of reflections internal to the structure made IIDT and resonant devices undesirably complicated choices for this work. Because the accurate control of transduction and reflection mechanisms separately is required to obtain good SPUDT action and for FEUDTs to operate properly, and because the effective nature of these quantities within a multilevel transducer structure such as the one developed in this work was also not known, the simpler GUDT structure was chosen for generation of low-loss devices in the current work.

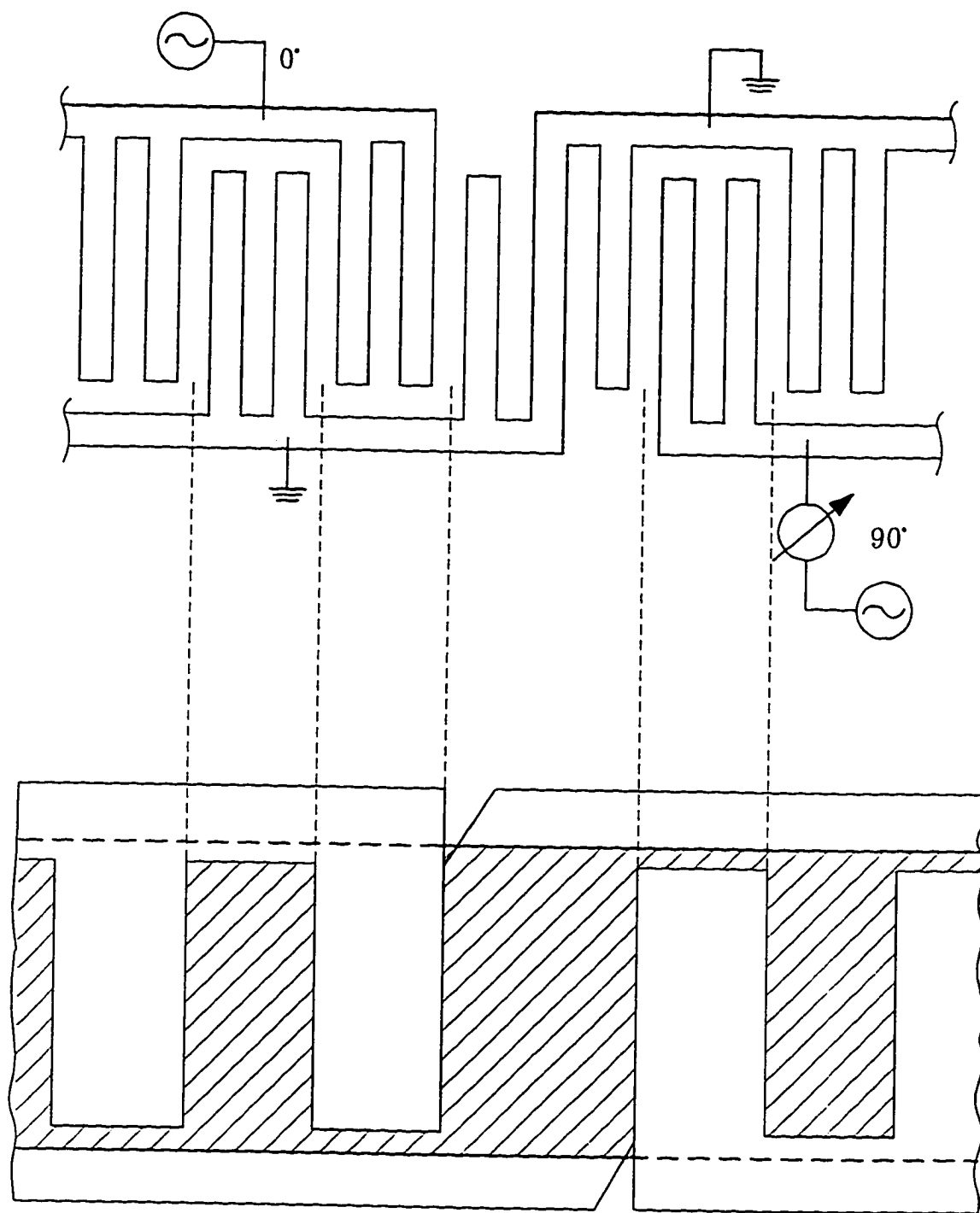


Figure 60. Two phase GUDT structure using half wavelength electrodes and a multilevel transducer structure.

Low-Loss Device Design

Devices were designed using simple two phase GUDTs [18], implemented with multilevel transducers using half wavelength electrodes as shown in Figure 60. The devices were designed to operate at a nominal fundamental frequency of 1.8 GHz. The fixed spatial offset of 90° between transducer sections was implemented on the first level metal, which was grounded throughout. The top level metal pattern consisted of two separate bond pads and sets of electrodes which were interdigitated relative to the first level metal. Since earlier devices at 100 and 500 MHz indicated that the interleaved electrode structure operates substantially better than the structure with a solid upper electrode, only interleaved transducers were built in this experiment. Because of the high operating frequency and the desire to utilize the simplest fabrication process possible while avoiding waveguiding effects within the devices, the transducers were designed to utilize aluminum roughly 1000 Å thick, with very narrow bus bars. These bus bars were fed by feeder bars, which in turn connected to bond pads large enough to bond to. This structure effectively distances the bond pads from the active area of the device, avoiding or reducing the effect of potential waveguiding.

The transducer section must be driven in quadrature, as shown in Figures 59 and 60. In order to achieve an accurate relative phasing at 1.8 GHz and above, the device sections were phased using external variable phase shifting circuitry, and combined using microwave range power splitters. Details of how a structure of this type can be used for harmonic performance can be found in [18], and the theory of operation at the fundamental frequency is presented in [76].

Experimental Results

Figure 61 shows the frequency response of a device consisting of two 1.8 GHz multilevel GUDTs with both transducers phased so that each is nominally unidirectional toward the other. The insertion loss when properly phased (but not ideally matched) is approximately 8.5 dB, demonstrating the applicability of the multilevel transducer structure to high frequency low-loss devices. It is unlikely that ideal matching would reduce the insertion loss more than 2 dB, based on VSWR measurements of other 1.8 GHz devices with similar transducers. Passband ripple is again due to reflections from additional ungrounded transducers on the die. It is interesting to realize that, had this

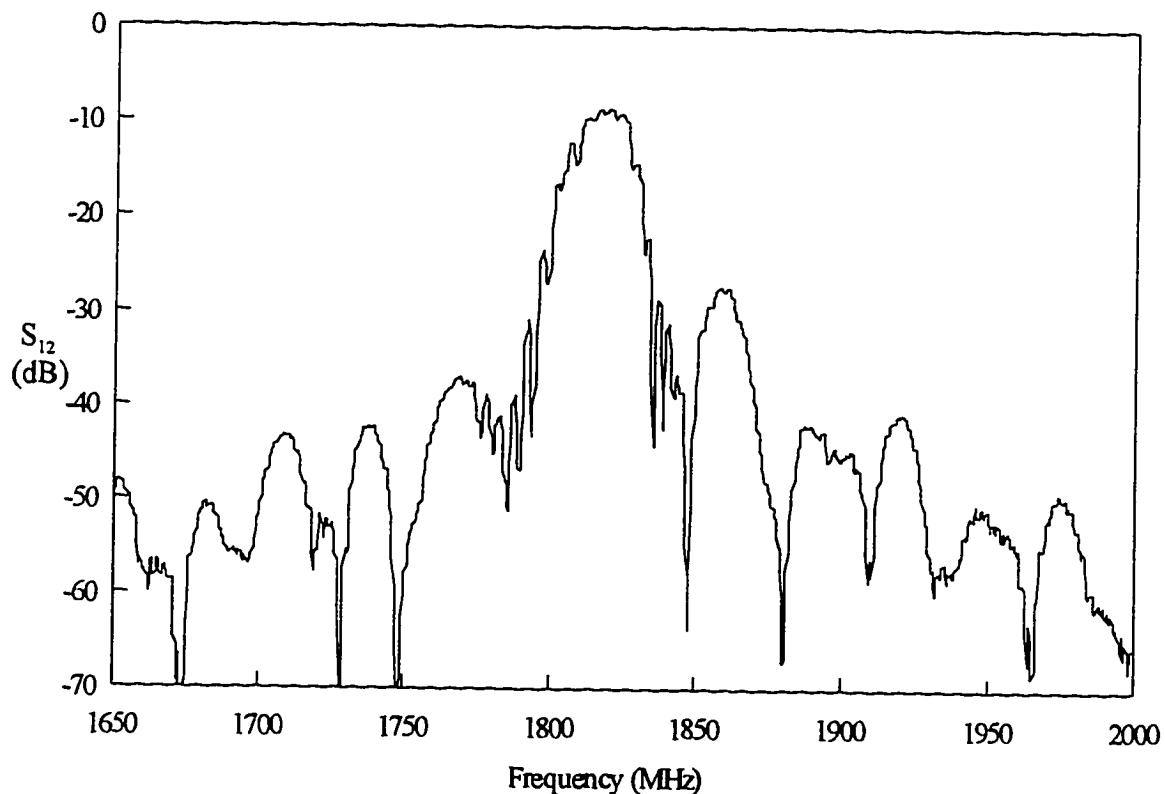


Figure 61. Frequency response of 1.8 GHz GUDT when properly phased for minimum insertion loss.

device been designed to operate at the third harmonic as in [18], a relatively low-loss SAW response could have been obtained at 5.4 GHz using a transducer with approximately 1 μm lines.

Figure 62 shows the response of the pair of GUDTs when both transducers are reverse phased. Note the clear notch in the passband at the device center frequency of approximately 1,827 MHz. Because this simple type of GUDT is only phased (or reverse phased) by the electrical network at one frequency, the notch is quite narrow. A variable length delay line, or phase shifter, was included in the external drive circuitry on each side of the device, so that the phasing could be optimized for each side independently.

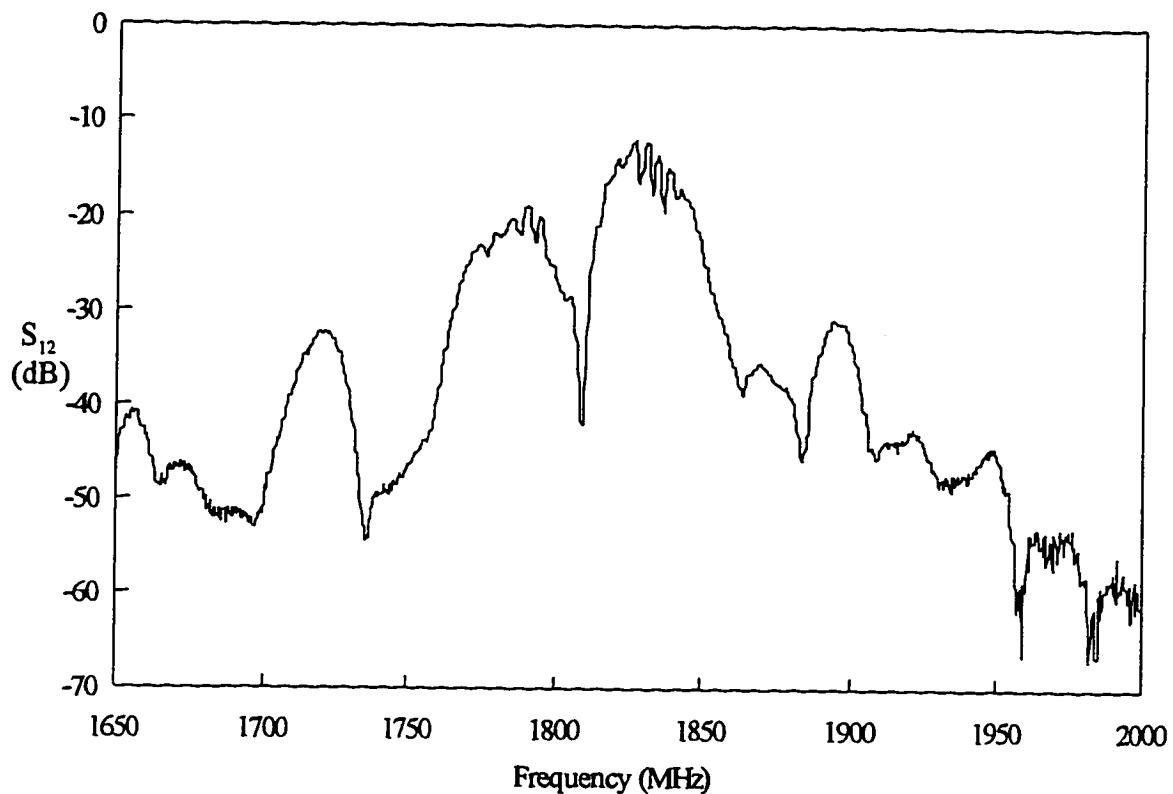


Figure 62. Frequency response of 1.8 GHz GUDT when reverse phased. Note the null in the passband.

Summary

A simple GUDT structure was implemented at 1.8 GHz using the multilevel transducer structure presented previously. Low-loss operation was achieved, with the device having unmatched insertion loss of 8.5 dB when properly phased. Forward and reverse phasing of this device was demonstrated.

The capability of this transducer structure to operate at high frequency with low loss has been demonstrated. More work will need to be done to achieve optimal low-loss performance, probably by using a structure other than a GUDT, like a SPUDT, where more control can be exercised over the unidirectional nature of the transducers.

CHAPTER 9

CONCLUSION

This work describes the development and implementation of a multilevel, half-wavelength transducer structure for high frequency SAW device fabrication. This transducer structure consists of a lower level metallization pattern containing a bus bar and half wavelength electrodes of one polarity, a thin silicon nitride dielectric insulating layer, and an upper level metal electrode or electrodes. Production of this transducer configuration requires only conventional SAW fabrication techniques, making it inherently more manufacturable than previously presented quasi-half-wavelength structures. One method for fabricating these devices requires no critical mask alignment steps, further enhancing manufacturability. This multilevel transducer structure is not inherently lossy, and can potentially be used in any common low-loss device configuration. Low-loss performance in the current work is demonstrated using a simple GUDT low-loss test structure.

In order to fabricate devices using the multilevel transducer structure, it was necessary to develop and refine several fabrication processes. Two different multilevel fabrication processes were used in this work. Both utilized standard photolithographic techniques and wet etching to generate the lower level metal patterns. Both processes

also utilized PECVD of silicon nitride films and RIE to generate the desired nitride patterns. The two processes differ principally in fabrication of the upper level metal electrode. In what has been referred to as the multilevel transducer fabrication process, a negative photoresist called Futurrex was used to define the desired metal pattern. A short oxygen plasma clean, e-beam evaporation of the upper level metal, and subsequent liftoff generated the desired upper level metal patterns. By comparison, the narrow-gap multilevel transducer fabrication procedure involved the use of AZ-5214, a dual-tone resist. Front side exposure of the wafer using a coarse mask was followed by an image reversal bake and back-side flood exposure of the wafer, using the first level metal as a mask for exposure. Devices were fabricated at frequencies up to 500 MHz utilizing both of these methods.

The quality and uniformity of the silicon nitride used as a dielectric insulating layer in these transducers was significant. A substantial amount of effort was expended refining and stabilizing the Si_3N_4 PECVD process, establishing the RIE process, and characterizing the nitride films. The PECVD was conducted using silane and ammonia as reactant gases. Tests performed over a three year period demonstrated the high level of reproducibility of the film deposition process. Under optimal deposition conditions, uniform films were obtained simultaneously on three wafers with 3 inch diameters. The nitride films were analyzed for composition using Auger Spectroscopy, IR Spectroscopy, and density measurements. All of these techniques indicated the films produced were high quality silicon nitride films, with stoichiometries of $\text{Si}_3\text{N}_{3.892 \pm 0.006}\text{O}_{0.05}$, nearing ideal silicon nitride. IR spectroscopy verified a low hydrogen content for these films. A RIE process was

developed using a plasma generated from a $\text{CF}_4/8.5\% \text{O}_2$ reactive gas mixture. This chemistry was selected to provide clean silicon nitride etching without deposition of films on the substrate surface observed with other plasma chemistries.

The silicon nitride films were characterized using a number of SAW devices and test structures. Quantities such as propagation loss and reflectivity were evaluated for films ranging from approximately 500 Å to approximately 3350 Å. This evaluation showed the very low SAW propagation losses, below 0.008 dB/λ for films less than 1500 Å thick, inherent to high quality silicon nitride films. Reflectivity per strip was also measured for Si_3N_4 on LiNbO_3 , and it was found that the reflectivity could be made as high as the reflectivity of metal strips on LiNbO_3 by using nitride films of up to $2\%(\lambda)$. The properties of low acoustic attenuation and high reflectivity make silicon nitride films desirable for use in acoustic devices requiring passivation, frequency tuning, reflective structures, and waveguides.

SAW devices utilizing multilevel transducers were fabricated at frequencies ranging from 100 MHz to 1.8 GHz. Control devices with split finger single level metallization were also fabricated and tested. Delay line device using unweighted multilevel transducers exhibited the expected $[\sin(x)/x]^2$ frequency response. Losses of unmatched devices generally exceeded approximately 20 dB. Multilevel devices which have solid metal pads as upper electrodes were shown to have less desirable performance characteristics than devices with interdigitated electrodes on the upper and lower levels. Apodization of the multilevel transducer was demonstrated using a 500 MHz filter.

In order to be able to analyze and predict the approximate performance of devices utilizing the multilevel transducers, it was necessary to characterize the properties of the transducers and develop a predictive model. The transducers were characterized by extracting equivalent circuit parameters for devices with frequencies ranging from 45 MHz to 1.8 GHz and with nitride film thicknesses ranging from 480 Å to 3350 Å. These equivalent circuit parameters were then used in a transmission line model to predict device performance.

To facilitate obtaining the equivalent circuit parameters, a parameter extraction technique was developed which is applicable for any interdigital transducer structure. This technique uses common S-parameter measurements and allows the unambiguous extraction of device parameters even in circumstances where the substrate properties such as k^2 and C_s are not known a priori. Good agreement was obtained between known and extracted values of k^2 and C_s for control devices on several substrates, and between experimental and predicted transducer impedances and admittances for devices with interleaved upper and lower electrodes and with nitride films less than 1000 Å thick. For devices with thick films and those with solid upper electrodes, agreement was not as good. A capacitive model was developed to describe the variation in extracted coupling with dielectric layer thickness and transducer frequency. Good correlation was observed between extracted and predicted values of coupling for 100 MHz and 500 MHz multilevel devices. Predicted values of coupling for 1.8 GHz devices were shown to be accurate when used in device modeling.

The equivalent circuit model, while useful for extraction, is not adequate for predictive purposes. A transmission line model was developed which treats each line and gap within the transducer as a transmission line, cascading these sub-models to yield transducer responses and subsequently cascading the transducer responses to obtain the overall device response. Good correlation was obtained between experimental and modeled responses for both conventional single level split finger transducer devices and devices using multilevel transducers, at frequencies ranging from 45 MHz to 1.8 GHz.

The multilevel transducer was shown to be a structure without significant inherent losses for thin nitride layers, and hence a potential candidate for use in numerous low-loss SAW device configurations. Low loss performance was demonstrated using a simple GUDT operating at a fundamental frequency of 1.8 GHz, and resulting in an unmatched loss of approximately 8.5 dB. Forward and reverse phasing of the unidirectional transducer was observed. The low-loss performance of this simple type of unidirectional transducer filter clearly indicates the potential for application of the multilevel transducer structure to high frequency low-loss SAW devices.

It is clear from this work that the multilevel transducer structures and processes developed hold promise for providing a manufacturable approach to extending the frequency range of SAW devices. Combining this approach with other techniques currently used to obtain high frequency responses, such as harmonic operation and utilization of specific substrates and wave propagation modes, can enable devices with linewidths near 1 μm to perform at frequencies substantially above 5 GHz. As wireless communications and other applications for SAW devices worldwide tend toward higher

frequencies, development of SAW devices with capabilities in these frequency ranges will help SAW remain the technology of choice for years to come.

Future Work

This work has demonstrated the feasibility and potential advantages of using a multilevel transducer structure in high frequency low-loss SAW devices. As with any new technology, there is a substantial amount of work left to be done to adapt this technique to commercial applications. Primarily this work will need to focus on several areas. First, effort will need to be placed on enhancing the simulation tools to include second order effects and to allow for the analysis of more general transducer and device structures. Having accurate predictive capabilities for a wide range of device structures utilizing multilevel transducers will allow for these structures to be used to their best advantage. Second, the multilevel transducer presents interesting opportunities for new device structures, including variations on SPUDTs, capacitively weighted devices, and others. Substantial effort should go into evaluating the potential opportunities these new structures would provide. Finally, and most significantly from a commercial point of view, the small-scale fabrication process developed in this work must be adapted to volume manufacturing. While the techniques involved in these processes are all conventional, substantial work remains to implement these processes in a manufacturing environment, and to conduct an appropriate sensitivity analysis to various process variations.

APPENDIX A
NARROW GAP MULTILEVEL TRANSDUCER FABRICATION PROCEDURE

NARROW GAP MULTILEVEL TRANSDUCER FABRICATION PROCEDURE

A robust air gap transducer fabrication process which avoids some of the concerns associated with photoresist sidewall profile uniformity in earlier narrow gap fabrication techniques was developed by the Solid State Devices and Systems Laboratory (SSDSL) of the University of Central Florida (UCF) [7]. This process, which completely avoids critical alignment steps, is described below, and is shown schematically in Figures 63 through 65.

First Level Metal Processing

YZ LiNbO₃ wafers with a diameter of 3 inches were coated with approximately 910 Å of aluminum using RF sputtering, then patterned with the first level metal geometry using conventional photolithographic and wet etch techniques. This process is shown schematically in Figure 63.

Photolithography

Standard photolithographic techniques were used to define a photoresist mask for wet etching of the aluminum film. Using Shipley 1400-27 photoresist, the wafers were coated and spun for 30 sec at 4000 rpm. They were then soft baked at 90 °C for 3

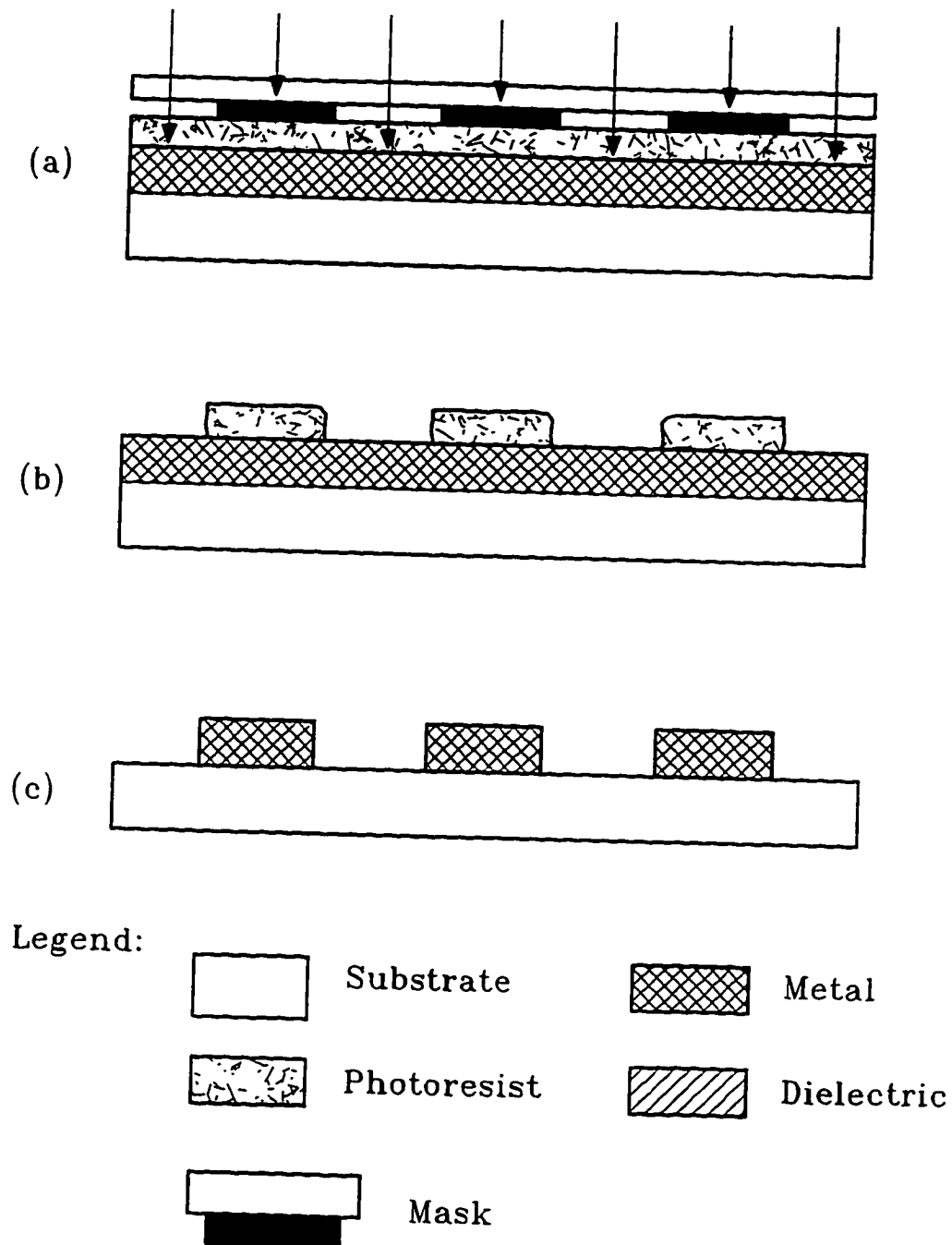


Figure 63. Fabrication process flow for first level metal. (a) exposure of photoresist to define desired metal pattern; (b) photoresist pattern protecting aluminum during wet etch process; (c) lower level metal pattern following aluminum etch and stripping of photoresist.

minutes on an aluminum transfer tray, and allowed to cool for at least 2 minutes. The photoresist coated wafers were then aligned and exposed on Karl Suss aligner using first level mask. Aligner operation is described below. Exposure required an average exposure time of 1.2 sec at a power density of 31.1 mWatt/cm², using a 405 nm light source. This represents a total dose of approximately 37.3 mJoules/cm². The exposed wafers were then developed in MIF-312 developer mixed 1:1 with deionized (DI) water (H₂O) until the field cleared, rinsed with DI H₂O to stop the development process, and blown dry with N₂. Develop time averaged approximately 1 minute 40 seconds.

Aluminum Etch Process

An aluminum etch was used consisting of 16 parts phosphoric acid, 1 part nitric acid, 1 part acetic acid, and 20 parts DI H₂O. The etch was heated to 35 °C, and the aluminum on the wafers was etched until 10 seconds past clearing of the field. Wafers were then rinsed with DI H₂O to stop the etch. Etch time averaged approximately 1.25 minutes for 900 Å of Al. The photoresist remaining on the wafers was then stripped using acetone, methanol, and DI H₂O, and the wafers were blown dry with N₂.

Aligner Operation

Prior to turning on the Karl Suss aligner, open the vacuum valve behind the machine. Turn on the small lamp using the switch on the small box to the left of the microscope. Turn on the lamp cooling gas and N₂ supply lines using the two lower toggle

switches, and turn on the aligner power. Turn on the lamp power, and wait until the lamp meter readout reaches 278 prior to using for exposure.

Load the mask by removing the mask holding chuck, turning the chuck upside down, placing the mask on the chuck so that the flat is to the right side of the machine, and push the mask vacuum button to secure the mask. Invert the chuck and mask assembly, insert the assembly into the aligner, and secure it by tightening the two front screws.

Load the wafer on the wafer chuck so that the wafer flat is to the right edge of the chuck, roughly parallel to the edge of the aligner housing beneath which the wafer chuck passes. Slide the wafer chuck to the left, under the mask.

Use the contact lever on the left side of the aligner to slowly raise the chuck, by rotating the lever from front to back, simultaneously turning the small front knob slowly clockwise to introduce some spacing between the wafer and the mask, so that when the contact lever is fully back, some space still remains between the wafer and mask. Slowly turn the front knob counterclockwise to raise the chuck until the wafer is grabbed by the mask, and then slowly turn the knob counterclockwise to raise the chuck to lightly contact the back of the wafer.

Now that the wafer and mask are in contact, the wafer can be exposed. However, generally the alignment needs to be adjusted, so the separation lever should be moved horizontally from the back to the front to introduce a separation between the mask and wafer. Adjust the x, y, and θ knobs for proper alignment, then push the separation lever back to place the wafer back in contact with the mask. Push the vacuum chamber button

to increase the contact between the wafer and mask, adjusting the small knob next to the chamber vacuum gauge to increase the vacuum in the chamber to over 5 Bar. Set the exposure time on the dial to the right value, and press the expose button to conduct exposure. Move the contact lever forward to allow the wafer to leave contact with the mask and to lower the chuck. Slide the wafer and chuck to the right and unload the wafer.

Once all exposures are completed, turn off the lamp and allow the gases to continue to flow to cool the lamp for at least 30 minutes. Failure to allow the lamp to cool properly may result in damage to the lamp.

Dielectric Layer Processing

After removing all photoresist, silicon nitride insulating films were grown over the patterned wafers in a modified Plasma Technology reactive ion etch (RIE) system (Model RIE-80), configured for plasma enhanced chemical vapor deposition (PECVD), using a combination of silane and ammonia. Details of the deposition process are given in Appendix D, and the effects of variation in deposition conditions on film quality and composition are discussed in Chapter 2. The nitride films were then patterned using conventional photolithography, and etched using a dry RIE process. This process is shown schematically in Figure 64.

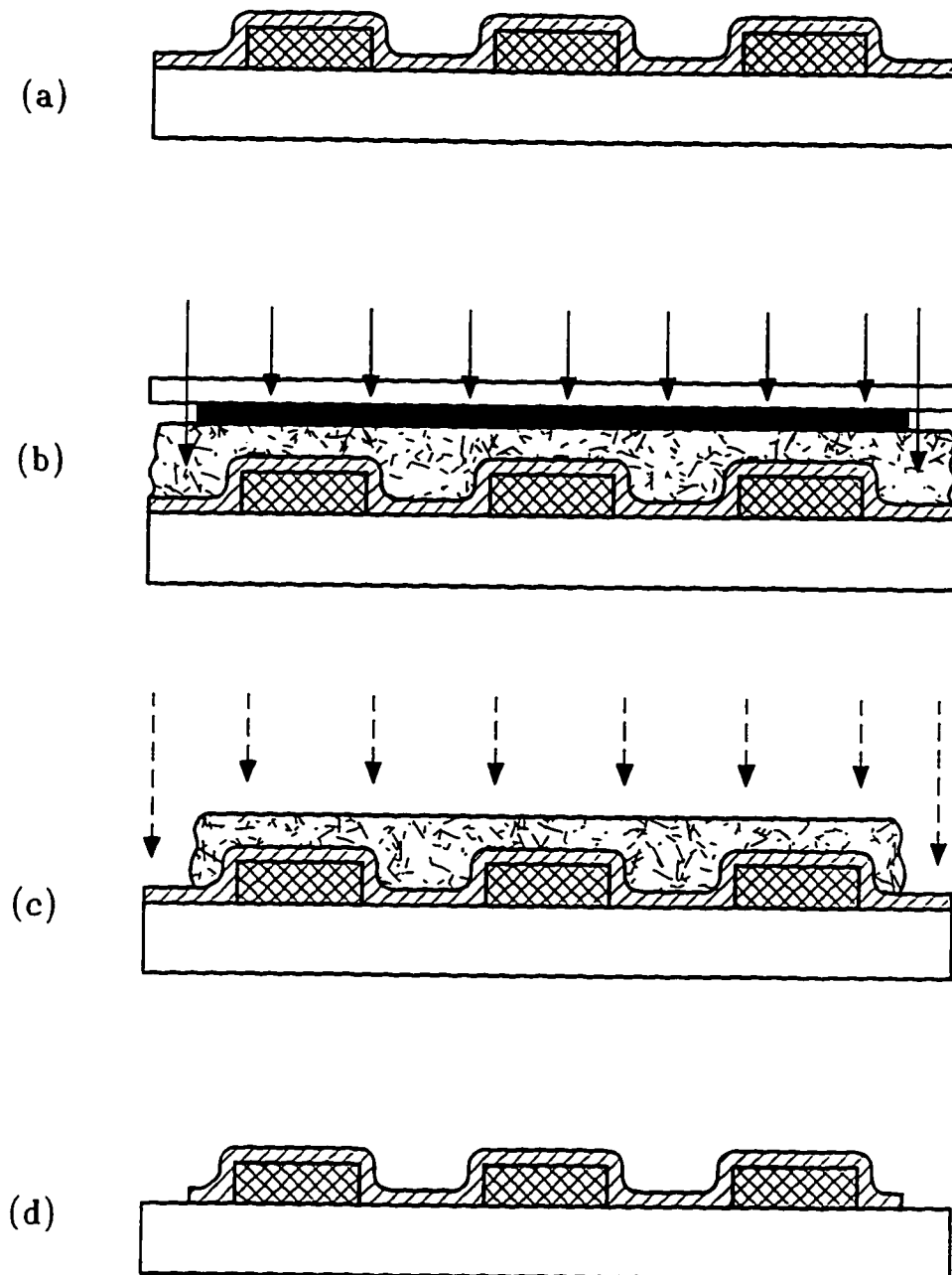


Figure 64. Fabrication process flow for dielectric pads. (a) Si_3N_4 layer following PECVD film deposition; (b) photolithographic definition of Si_3N_4 pad; (c) RIE of the Si_3N_4 film in regions surrounding the desired pad; (d) device with Si_3N_4 pad following RIE process and photoresist stripping.

Photolithography

Standard photolithographic techniques were used to define a photoresist mask for reactive ion etching (RIE) of the Si_3N_4 . Hexamethyldisilazane (HMDS) was used to enhance adhesion of the photoresist to the nitride film during this step. The HMDS was spun onto the wafers at 4000 rpm for 30 seconds, and the wafers were placed directly on a preheated aluminum plate inside an oven and baked at 90 °C for 60 seconds. The wafers were then cooled for at least 2 minutes, coated with Shipley 1400-27 photoresist by spinning for 30 sec at 4000 rpm, and soft baked for 3 minutes at 90 °C on an aluminum transfer tray. The wafers were then aligned on the Karl Suss aligner using the second level mask, and exposed for an between 1.4 and 2.5 seconds. The exposed wafers were then developed in either MIF-312 developer mixed 1:1 with DI H_2O or in Hoechst Celanese AZ developer mixed 1:1 with DI H_2O . Develop times were approximately 65 seconds in MIF-312 and ranged from 1 minute to 3 minutes in AZ developer, depending on exposure. The developed wafers were then hard baked at 120 °C for 10 minutes on an aluminum transfer tray, and allowed to cool to room temperature prior to etching the nitride films as described below.

Reactive Ion Etch Process

Reactive ion etching of the silicon nitride films was done in the same Plasma Technology reactive ion etch (RIE) system (Model RIE-80) used previously for PECVD of the films, now configured for RIE. Initial RIE work used C_2F_6 as the reactant gas, with

a flow rate of 15 sccm¹ on the gas 1 channel, chamber pressure of 30 mTorr prior to striking the plasma, which increased to 33 mTorr following establishment of the plasma, and RF power of 100 Watts. The silicon nitride films used in this study showed an etch rate in the C₂F₆ plasma of approximately 6 Å/sec, as discussed in Chapter 2. During the RIE process, however, a thin brownish film was deposited on the regions of the wafer not covered with photoresist. The identity of this film was not determined, but it had a texture somewhat like a thinly spread viscoelastic film, and it was not possible to remove it using either oxygen plasma cleaning or ordinary washing of the wafer with acetone, methanol, and DI. It was postulated that this film might be the result of a lack of oxygen available during the RIE process resulting in the deposition of a form of fluorocarbon on the wafer surface. Whatever this substance was, it did not seem to adversely affect the finished device performance.

To stop the deposition of this unidentified film, the RIE process was changed to one using an 8.5% O₂ in CF₄ reactant gas mixture. The silicon nitride films used in this study showed an etch rate of approximately 18 Å/sec in this plasma with a gas flow rate of 100 sccm, RF power of 50 Watts, pre-plasma pressure of 250 mTorr, and with sample temperature maintained at approximately 25 °C by maintaining coolant flow to the bottom RIE electrode. Using a gas flow rate of 25 sccm, RF power of 100 Watts, and pre-plasma pressure of 55 mTorr resulted in a silicon nitride etch rate of approximately 25 Å/sec.

¹ It should be noted that all references to gas flow rates are as measured on the system digital meter monitoring flow through the mass flow controllers. Because the controllers are not all calibrated for operation with the gases used, the actual gas flows utilized will depend on the gases in question. The conversions used in determining the actual gas flow rates are given in Appendix C.

RIE Operation

The Plasma Technology RIE system was operated at room temperature when in the RIE mode. Coolant water, set to 25 °C, was left circulating through the system at all times. The main power to the system was also left on. When starting the system up, first verify that the vent valve in the rear of the system has been closed tightly. Next, plug in the mechanical pump, and open the mechanical pump purge line to allow N₂ purging of the mechanical pump. Verifying that the chamber is closed, turn on the mechanical pump by pressing the "pump" button on the front panel. Verify that the chamber pressure is rapidly dropping. A major leak will cause the chamber pressure to not drop rapidly, and the mechanical pump is likely to trip its circuit breaker and turn off. Should this happen, the breaker can be reset in the utility corridor between the two cleanroom areas. Holding down the chamber open/close button and moving the chamber lever toward "close" while the pump starts to evacuate the chamber generally guarantees a tight seal.

While the chamber is pumping down, verify that the appropriate reactant gas cylinder is connected to the gas 1 line, and that the positions of the two stop valves is such that the cylinder gas will flow, not the O₂. Open the cylinder valve and dial in the desired pressure on the cylinder's regulator valve. Once the chamber pressure has dropped below 20 mTorr, turn on gas 1, which is connected to the reactant gas mixture to be used for RIE, and check the no-flow reading on the digital meter. Generally this will be below 003. Determine the appropriate meter reading to yield the desired net gas flow, and turn the gas 1 dial to the right until this setting is achieved. Switch the meter to readout chamber pressure, and monitor pressure until it drops to 55 mTorr or below. Throttle the roughing

valve to adjust the chamber pressure to the desired process pressure. Set the timer to the desired etch time, or to a long enough time to establish a good plasma for the first shot of each session. Turn on the RF power supply, making sure the setting is on "Auto". Turn on the RF power by pressing the button on the system front panel. Check the forward power on the power meter, and increase to 50 Watts by turning the power knob on the front panel. Check the reflected power and tune to zero while the plasma is well established. Verify that the plasma is the proper color (dull bluish white for a pure O_2 plasma, bright blue for C_2F_6 , light blue for CF_4/O_2 , bright pink for NH_3 and N_2). This process of verifying the operation of the plasma should be conducted at least once before use for etching each day the system is in use. Once the plasma looks good, turn off the RF power at the front panel button, turn off the gas 1 flow, and allow the chamber to pump down to below 20 mTorr. At this point, push the pump button on the front panel to stop pumping out the chamber, and push the vent button twice to introduce N_2 into the chamber to increase chamber pressure back to the pressure of the surroundings. The chamber can then be opened by pushing down on the open/close button on top of the system, and simultaneously pushing the lever toward the open position. Wafers can then be loaded onto the bottom electrode of the system for RIE, or if the previous run was an actual etch rather than a system verification run, the etched wafers can be removed from the system and new wafers placed in the system. The process is then repeated for all wafers requiring RIE.

When all RIE operations for the day have been completed, the system cylinders used for reactant gases should be closed and the lines should be pumped out back to at

least the mass flow controllers. The cylinder is closed by shutting the valve on top of the cylinder and backing off the regulator valve for the cylinder. The bypass valves in the gas distribution cabinet can be briefly opened and closed repeatedly to pump out the lines more rapidly. Once the gas line pressure has dropped below 20 mTorr, the gas flow is turned off, and the system is pumped down to below 200 mTorr. The RF power supply is turned off, and the mechanical pump is unplugged and the mechanical pump purge valve closed. Finally, the line is vented by opening the vent valve behind the system. This valve should be left closed.

Top Level Metal Processing

The top level metal patterns were generated using an image reversal photolithography, electron-beam evaporation of aluminum, and liftoff. This process is shown schematically in Figure 65.

Wafer Preparation

Following reactive ion etching of the nitride pattern, the photoresist was stripped by washing with acetone, methanol, and DI, and the wafers were blown dry with N₂. A residue of photoresist remained, particularly along the edges of the nitride film structures, and an O₂ plasma clean was performed to remove remaining residue. The O₂ plasma clean was conducted following the RIE operation guidelines discussed above, with the gas 1 line valves configured to deliver O₂ rather than a canister hydrocarbon gas. The O₂ flow used was approximately 20 sccm, and the power was either 50 Watts or 100 Watts. System

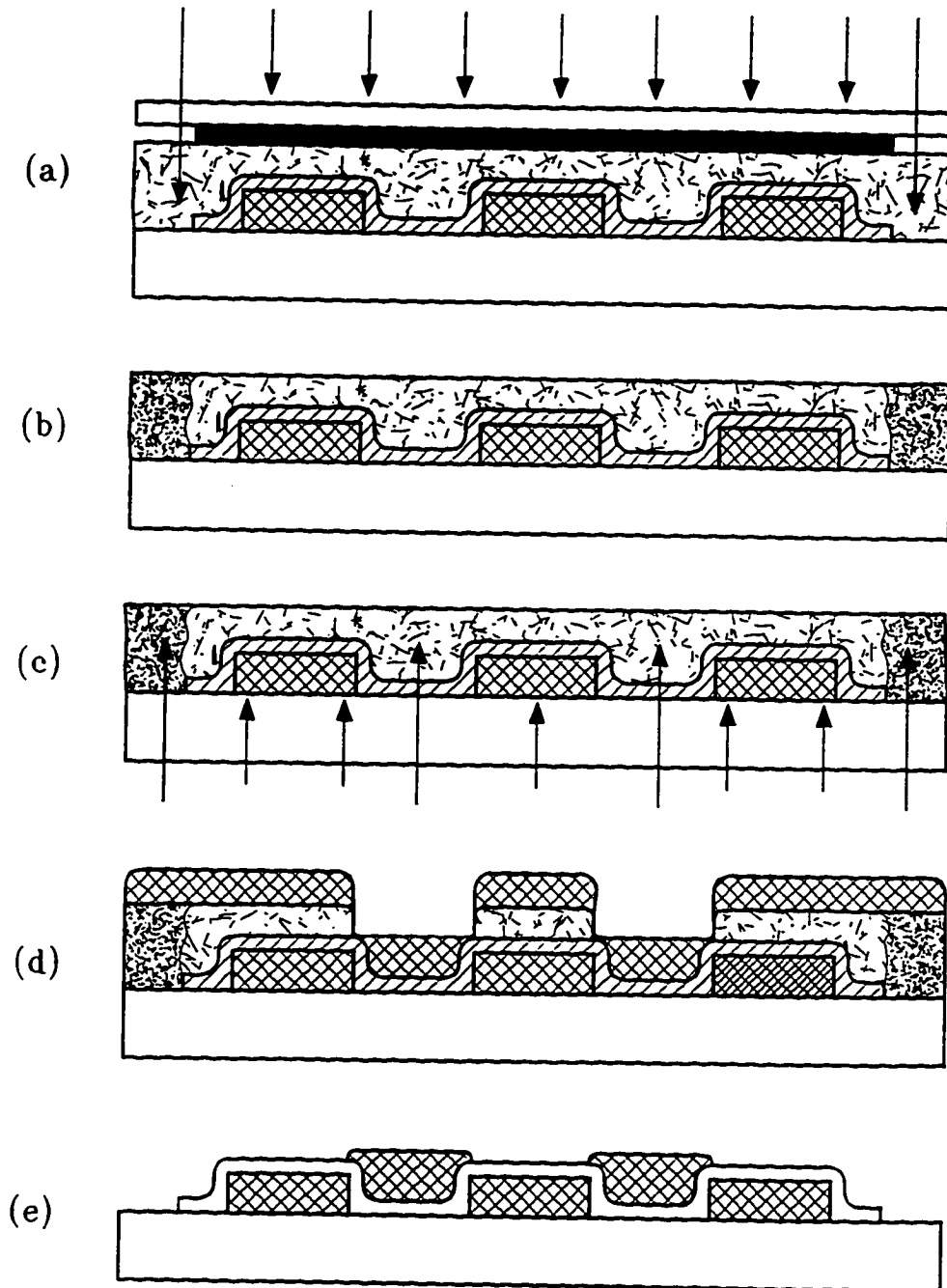


Figure 65. Fabrication process flow for top level metal. (a) Field exposure; (b) Change in photoresist following image reversal bake; (c) Flood exposure from back of wafer utilizes first level metal as a mask; (d) Evaporation of top level metal following photoresist develop step; (e) Final device structure following liftoff.

pressure was either left at the base system pressure with gas flow of approximately 80 mTorr, or was throttled to between 225 mTorr and 280 mTorr. A plasma clean time of 10 minutes was sufficient when operating at 100 Watts and 80 mTorr, while lower power settings required longer clean times to remove the residual hard baked photoresist.

Photolithography

The top level metal patterns were to be formed by a novel liftoff process which requires image reversal, so Hoescht-Celanese AZ-5214, a dual-tone resist, was used for this level. HMDS was used to enhance adhesion of the photoresist to the nitride film during this step. The HMDS was spun onto the wafers at 4000 rpm for 30 seconds, and the wafers were placed directly on a preheated aluminum plate inside an oven and baked at 90 °C for 60 seconds. The wafers were then allowed to cool for at least 2 minutes, coated with AZ-5214 photoresist by spinning for 30 sec at 3000 rpm, and soft baked for 3 minutes at 90 °C on an aluminum transfer tray. The wafers were then aligned on the Karl Suss aligner using the second level mask again, and exposed for 3 seconds at approximately 32 mW/cm². This exposure forms an acidic compound in the exposed regions of the resist, which if placed into AZ developer, a highly basic solution, would cause these regions to develop away. Instead, the exposed wafers were baked at 120 °C for 3 minutes, activating inhibitors which neutralize the acidic compound in the exposed resist, preventing the resist from developing away. These steps are shown schematically in figure 65 (a) and (b), where the dark photoresist regions indicate photoresist which has been image reversed through the exposure and baking process. Each wafer was then

cooled to room temperature, positioned face down on a non-reflective black mat placed on top of the aligner chuck, and back side exposed using a flood exposure for 8 seconds at approximately 32 mW/cm². As shown in figure 65 (c), the first level metal pattern acts as a mask for the photoresist during the flood exposure. The field regions of photoresist which were previously exposed and reversal baked were unaffected by the flood exposure, as were the regions of unexposed photoresist under the first level metal pattern, which consequently were left unexposed during the flood exposure. The regions of previously unexposed photoresist which were not covered by the first level metal were exposed during the flood exposure, and were then ready to be developed away. While unexposed photoresist will also develop away in developer, it does so at a much slower rate than exposed photoresist. Following the flood exposure, the wafers were developed for approximately 45 seconds in Shipley 351 developer mixed 1:5 with DI H₂O. The developed wafers were rinsed with DI H₂O, and blown dry with N₂. An oxygen plasma clean was conducted for 1 minute at 50 Watts with an O₂ flow rate of 22 sccm and pressure of 80 mTorr to remove any residual photoresist. The wafers were then inspected to verify the quality of the photolithography prior to metal deposition and liftoff.

Metal Deposition and Liftoff

A layer of aluminum approximately 900 Å thick was deposited using e-beam evaporation, as shown in Figure 65 (d). Details of the evaporation process are given in Appendix D. Liftoff was then performed by immersing the wafers in acetone for times ranging from 20 to 40 minutes. Slight agitation was used, and the wafers were

periodically transferred into dishes of clean acetone to prevent aluminum chips from resettling onto the wafer surface. Ultrasonic agitation was found to provide more thorough liftoff, particularly for fine geometries. Following liftoff, the wafers were rinsed with acetone, methanol, and DI, and blown dry with N₂. The finished transducer structure, as shown in Figure 65 (e), can allow for inter-electrode gaps which are very small to nonexistent. The nitride layer makes the gap size and uniformity non-critical to device operation. Finished wafers were inspected, cut into die using a diamond saw, mounted onto headers, and tested.

APPENDIX B

MULTILEVEL TRANSDUCER FABRICATION PROCEDURE

MULTILEVEL TRANSDUCER FABRICATION PROCEDURE

The half-wavelength electrode multilevel transducers described in this work were fabricated using a procedure which involves only standard processes. This procedure is described below, and is shown schematically in Figure 66.

First Level Metal Processing

YZ-LiNbO₃ wafers with a diameter of 3 inches were coated with 900 to 1500 Å of aluminum using RF sputtering, then patterned with the first level metal geometry using conventional photolithographic and wet etch techniques. Individual process parameters were adjusted to yield the desired line to space ratios on different devices.

Photolithography

Standard photolithographic techniques were used to define a photoresist mask for wet etching of the aluminum film. The process utilized Shipley 1400-27 photoresist, and is identical to the first level photolithography process used in fabrication of narrow gap devices, described in Appendix A. Operation of the aligner used in this fabrication process is also described in Appendix A.

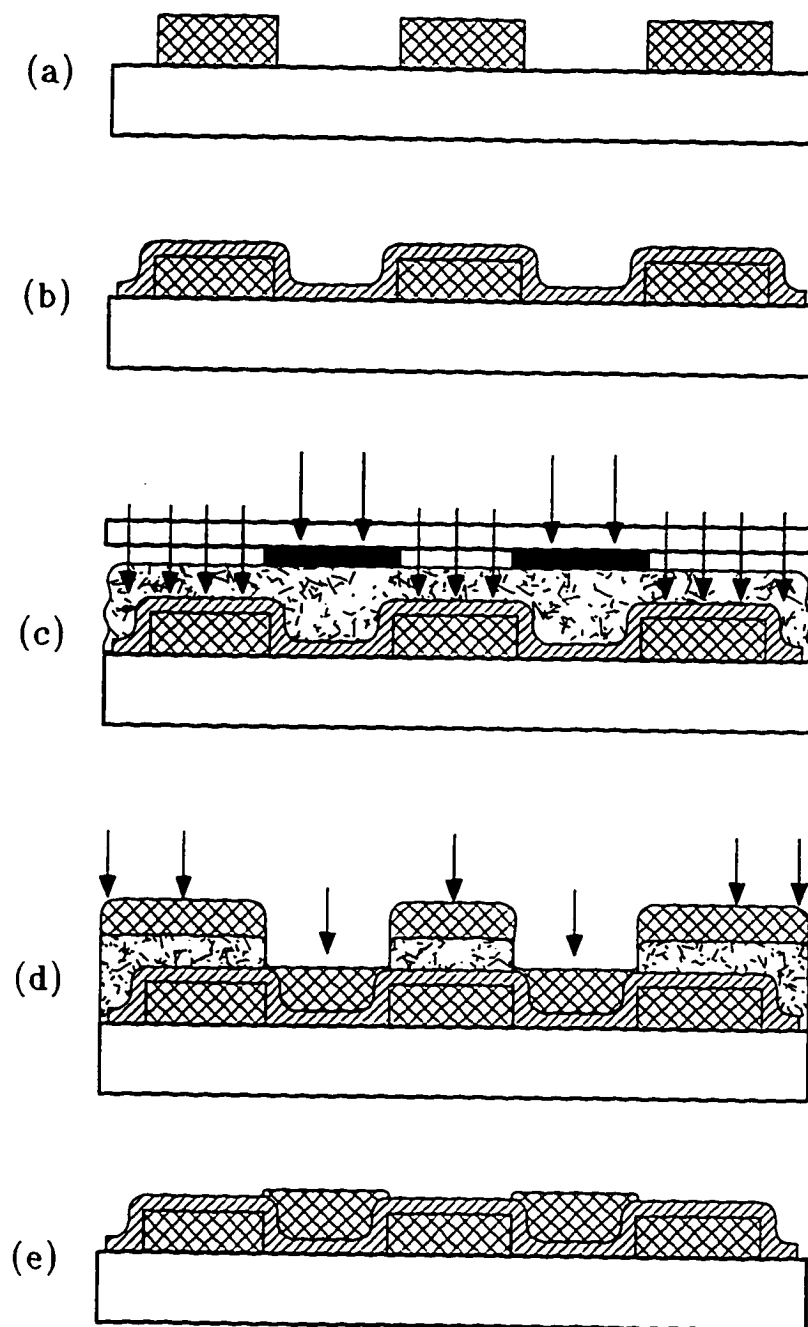


Figure 66. Multilevel transducer fabrication process flow. (a) Lower metal pattern; (b) Si_3N_4 pad following PECVD film deposition, photolithography, and RIE steps; (c) Mask alignment and exposure of negative photoresist coated wafer; (d) Evaporation of top level metal; (e) Final device structure following liftoff

Aluminum Etch Process

The aluminum etch process described in Appendix A for use in fabrication of narrow gap devices was also used for etching the first level metal pattern for the multilevel devices. Following etching of the aluminum, the photoresist remaining on the wafers was stripped using acetone, methanol, and DI H_2O , and the wafers were blown dry with N_2 .

Dielectric Layer Processing

After removing all photoresist, silicon nitride insulating films were grown over the patterned wafers via PECVD using a combination of silane and ammonia. Details of the deposition process are given in Appendix D, and the effects of variation in deposition conditions on film quality and composition are discussed in Chapter 2.

Photolithography

As described in Appendix A for processing of the dielectric layer in narrow gap devices, standard photolithographic techniques were used to define a photoresist mask for RIE of the Si_3N_4 in the multilevel transducers. HMDS was again used to enhance adhesion of the photoresist to the nitride film during this step, followed by the Shipley 1400-27 photoresist coating, exposure, develop, and hard bake process described in Appendix A.

Reactive Ion Etch Process

Reactive ion etching of the silicon nitride films was again conducted in a Plasma Technology RIE system (Model RIE-80) configured for RIE. Operation of this system in RIE mode is described in Appendix A. The RIE process used an 8.5% O₂ in CF₄ reactant gas mixture. The silicon nitride films used in this study showed an etch rate of 14-18 Å/sec in this plasma with a gas flow rate of 100 sccm, RF power of 50 Watts, pre-plasma pressure of 250 mTorr, and with sample temperature maintained at approximately 25 °C. Using a gas flow rate of 25 sccm, RF power of 100 Watts, and pre-plasma pressure of 55 mTorr resulted in a silicon nitride etch rate of approximately 25 Å/sec.

Top Level Metal Processing

Wafer Preparation

Following reactive ion etching of the nitride pattern, the photoresist was stripped by washing with acetone, methanol, and DI, and the wafers were blown dry with N₂. A residue of photoresist remained, particularly along the edges of the nitride film structures, and an O₂ plasma clean was performed to remove remaining residue. The O₂ plasma clean was conducted following the RIE operation guidelines discussed in Appendix A. The O₂ flow used was approximately 20 sccm, and a plasma clean time of 10 minutes was utilized with an RF power of 100 Watts.

Photolithography

Since the top level metal patterns were to be formed by liftoff, a different resist and photolithography process was used for this level. The wafers were spin coated with Futurrex NR8-1000, a negative photoresist. For line sizes over 2 μm , the resist was spun at 3000 rpm for 30 seconds, yielding a resist thickness of approximately 1300 Å. High frequency devices having 0.9 μm lines required thinner resist, so the NR8-1000 was spun at 4000 rpm for 30 seconds instead. The coated wafers were then baked on aluminum transfer trays at 130 °C for 90 seconds, and removed on the trays to room temperature to cool for a minimum of 5 minutes.

The coated wafers were then aligned and exposed from the top using a mask which defined both devices with solid upper electrode pads and devices with interdigitated upper electrodes requiring more careful alignment. Exposures of 4 seconds at approximately 31.8 mW/cm² were used for the low frequency devices, while exposures of 3 seconds gave the best results for the devices with 0.9 μm lines. Futurrex developer was used full strength to develop the resist, with an average develop time of approximately 50 seconds at room temperature. Developed wafers were rinsed gently with DI H₂O to stop the develop process, and blown dry with N₂. An oxygen plasma clean was conducted for 1 minute at 50 Watts with an O₂ flow rate of 22 sccm and pressure of 80 mTorr to remove any residual photoresist. The wafers were then inspected to verify the quality of the photolithography prior to metal deposition and liftoff.

Metal Deposition and Liftoff

A layer of aluminum approximately equal in thickness to the first layer was deposited using e-beam evaporation. Details of the evaporation process are given in Appendix D. Liftoff was then performed by immersing the wafers in acetone for times ranging from 30 minutes for large electrode geometries to approximately two hours for 0.9 μm electrodes. Slight agitation was used, and the wafers were periodically transferred into dishes of clean acetone to prevent aluminum chips from resettling onto the wafer surface. Ultrasonic agitation was found to provide more thorough liftoff, particularly for fine geometries. Following liftoff, the wafers were rinsed with acetone, methanol, and DI, and blown dry with N_2 . Finished wafers were inspected, cut into die using a diamond saw, mounted onto headers, and tested.

APPENDIX C

SILICON NITRIDE PECVD SYSTEM AND PROCEDURE

SILICON NITRIDE PECVD SYSTEM AND PROCEDURE

System Description

The silicon nitride insulating films used in this work were grown in a modified Plasma Technology reactive ion etch (RIE) system (Model RIE-80), configured for plasma enhanced chemical vapor deposition (PECVD). Whether in RIE or PECVD mode, the system has four main sections, the gas supply system, the gas distribution panel, the vacuum system, and the main system. These sections are illustrated in the system block diagram shown in Figure 67 and brief descriptions of each section are given below.

System operation in the PECVD mode is discussed below, and operation in the RIE mode is described in Appendix A.

Gas Supply System

The reactive gases used for PECVD of silicon nitride films in this work are ammonia (NH_3) and a 3% silane (SiH_4) in He mixture. Both gases are of certified by the supplier as having 99.999% purity. Silane is a highly reactive pyrophoric gas which produces a spark or flame upon exposure to oxygen. Since SiH_4 is potentially explosive, the system utilizes stainless steel tubing and vacuum seal tube fittings, and is equipped with a high pressure nitrogen (N_2) purging system to ensure adequate system purging prior

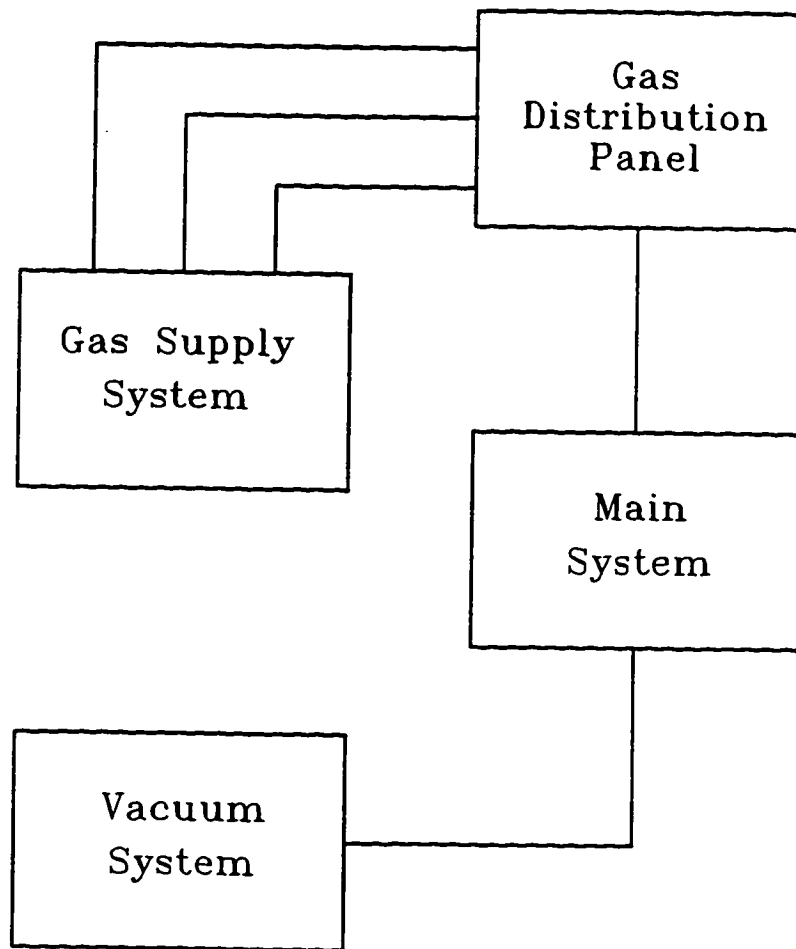


Figure 67. RIE/PECVD system block diagram

to introduction of SiH_4 . Two Semi Gas Systems Inc. gas cabinets are used for safety purposes, one housing the silane cylinder and the other housing the NH_3 gas cylinder. Each cabinet also contains a N_2 cylinder and purge system. The gas supply system for each gas is identical, and is shown schematically in Figure 68. The silane reactive gas cylinder is equipped with an emergency shut off valve which closes when a sudden high gas flow is detected. Two process gas supply lines run from the gas supply system to the gas distribution panel described below.

Gas Distribution Panel

The gas distribution panel shown in Figure 69 houses three mass flow controllers, labeled MFC1, MFC2, and MFC3, along with bypass valves. The mass flow controllers control the flow of gas 1, gas 2, and gas 3, respectively. MFC1 is calibrated for flow of N_2 . Since this controller was used for N_2 , O_2 , C_2F_6 , or $\text{CF}_4/8.5\% \text{ O}_2$ flow in various portions of this work, a flow rate conversion was required to relate the actual reactant gas flow rate to the flow controller meter output [34]. MFC2, which controls the flow of the silane process gas, is calibrated for 100% silane flow. Since the reactant gas used in this work was 3% SiH_4 in He, a flow rate conversion was also required for SiH_4 flow. These flow rate conversions are shown in Table 3 below [34], and the actual gas flow is given by the flow meter controller reading, in sccm, multiplied by the appropriate flow rate conversion. MFC3, which controls the flow of the NH_3 reactant gas, is calibrated for NH_3 flow. Thus, the flow rate displayed on the digital flow controller meter when gas 3 is selected represents the actual flow of NH_3 in sccm. All flows discussed elsewhere in this

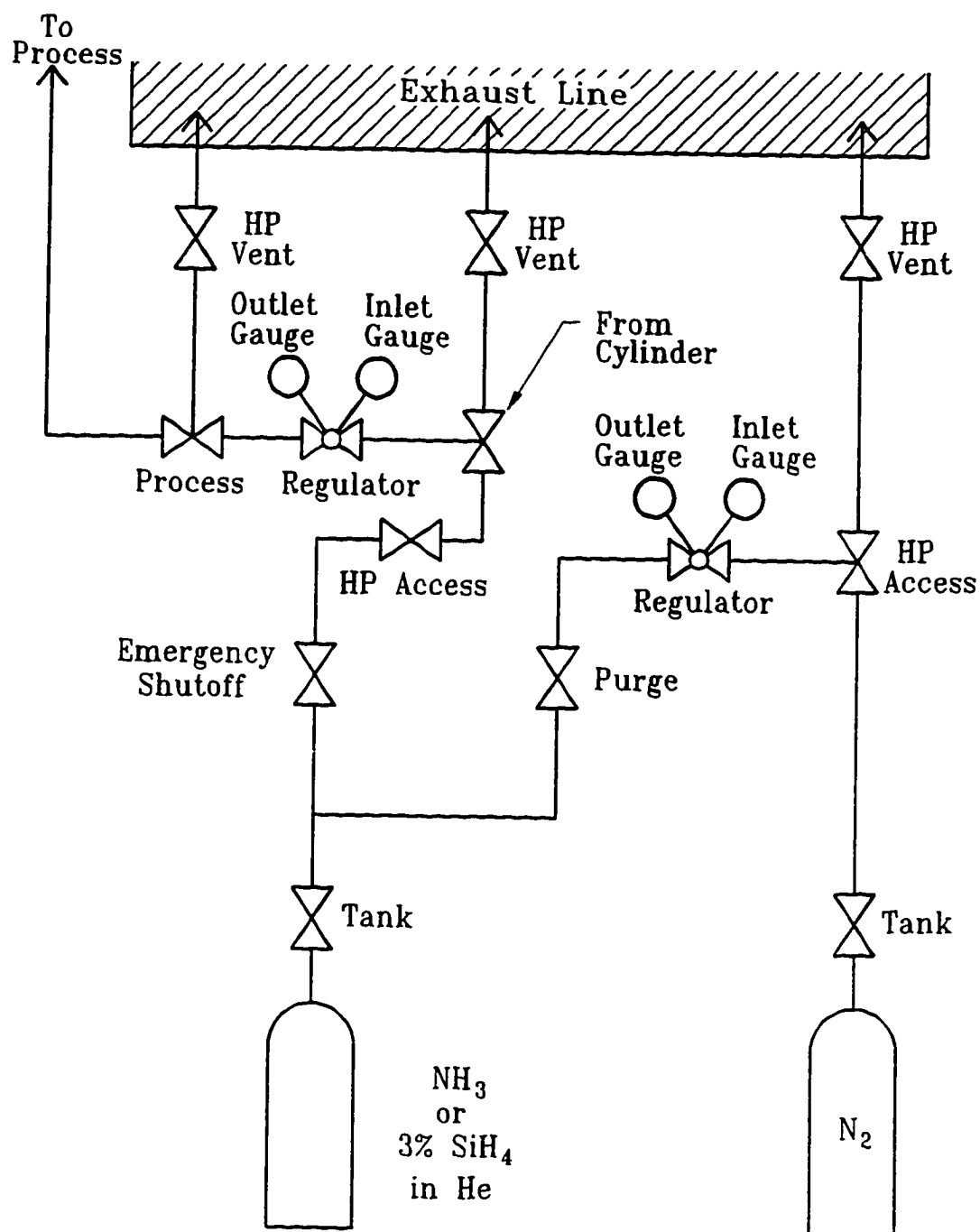


Figure 68. RIE/PECVD gas supply system

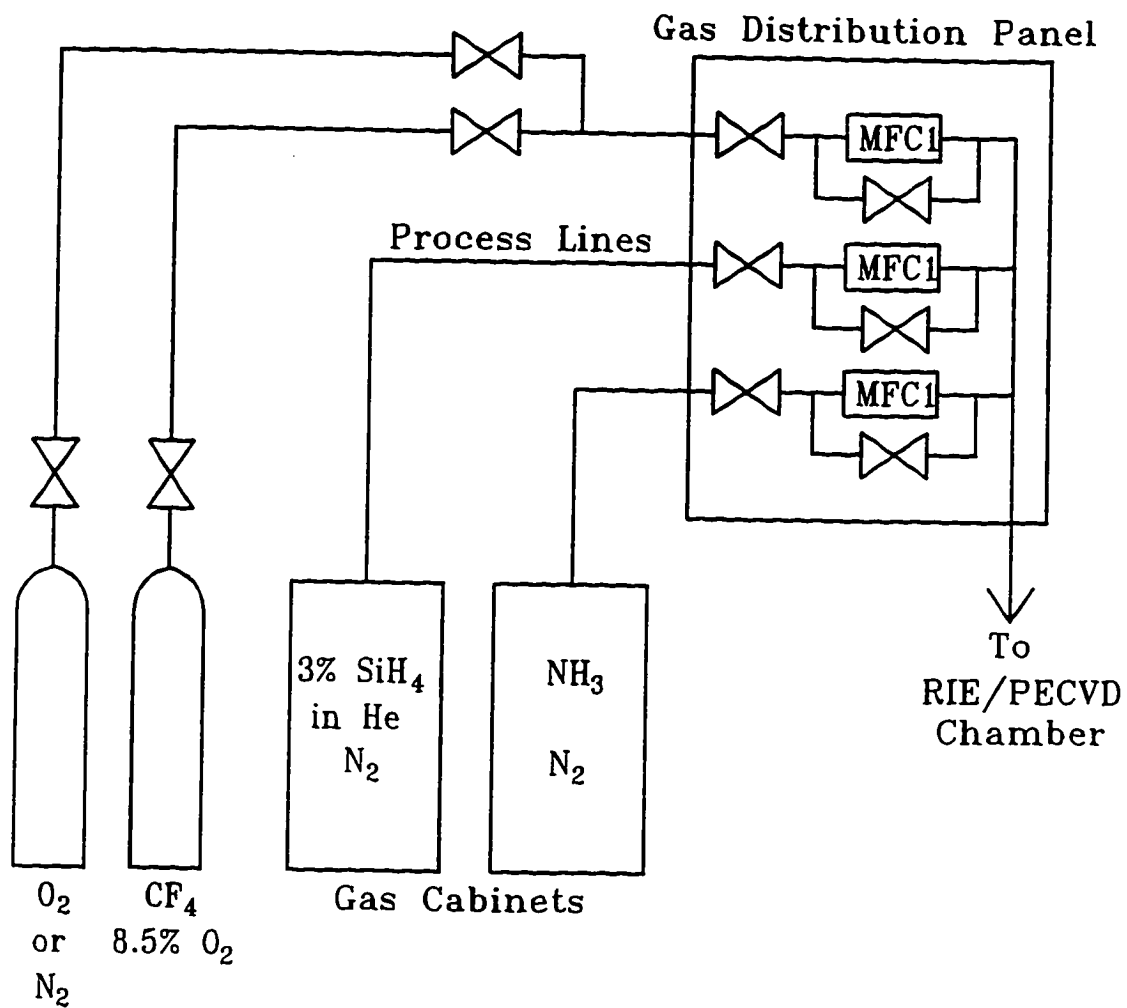


Figure 69. RIE/PECVD gas distribution system

document refer to the digital meter readout unless expressly stated otherwise, and the actual flow depends on the gas and mass flow controller combination used.

Table 3

Flow Rate Conversion Chart for RIE & PECVD Gases

Gas	N ₂	SiH ₄	O ₂	CF ₄ 8.5% O ₂	C ₂ F ₆	He 3% SiH ₄
Correction Factor (N)	1.0000	0.8800	1.0000	0.8800	0.8800	1.0352
Density at 0 °C (ρ)	1.2500	1.4330	1.4270	3.9260	6.1570	0.2162
Specific heat (C _p)	0.2485	0.3189	0.2193	0.1654	0.1843	1.0576
ρC _p	0.3106	0.4569	0.3129	0.6493	1.1347	0.2287
Flow Meter Calibration Gas (cal)	N ₂	SiH ₄	N ₂	N ₂	N ₂	SiH ₄
Flow rate conversion (ρC _p (cal)*N(gas))/ (ρC _p (gas)*N(cal))	1.0000	1.0000	0.9926	0.4209	0.2409	2.3502

Note. Source [34]

Vacuum System

The vacuum pump system has two pumps, a mechanical roughing pump and a high vacuum molecular drag pump (MDP). The mechanical roughing pump is a rotary vane pump capable of reducing chamber and line pressure to approximately 3 mTorr. The Alcatel 5030 CP MDP has a higher pumping speed than the mechanical pump, and utilizes an impeller to direct molecules toward the drag pump for increased pumping efficiency. The MDP has a rotational speed of 27,000 rpm, and can operate at pressures down to 1×10^{-6} Torr. An Alcatel CFF 450 Turbo drives the impeller rotation. Water cooling and

nitrogen purge lines are required for operation of the MDP with corrosive gases. Cooling water maintained at 25 °C is recirculated using a Neslab Coolflow CFT-33 refrigerated recirculator. As shown in Figure 70, the vacuum lines have several valves external to the main system, and two internal to the system. External valves are the roughing valve, the foreline valve, the MDP valve, and the vent valve. Internal to the main system are the N₂ vent valve and the chamber gate valve. Operation of the vacuum system is described under system operation for the RIE and PECVD modes. When configured for PECVD, the current system is capable of achieving a background pressure of 2×10^{-5} Torr in the chamber prior to flowing the process gases, with the MDP in use. Most depositions did not utilize this high a vacuum, starting the gases flowing at around 2 mTorr or below.

Main System

The main system consists of the RIE/PECVD chamber, a power supply and RF generator, power supply impedance matching circuits, temperature control circuitry, process logic and safety interlock circuitry, and a recirculating chiller, as illustrated in Figure 70.

When configured for either RIE or PECVD, the system chamber is a parallel plate reactor. The water cooled upper electrode plate is 24 cm in diameter and uses a "shower head" assembly with 17 holes within a diameter of 7.6 cm to uniformly distribute the process gases. The lower plate is 24 cm in diameter, with a 95% uniformity diameter of approximately 15 cm, and can be water cooled or heated with the substrate heater to 400 °C. The RF power, which operates at 13.56 MHz, can be connected to either the top or

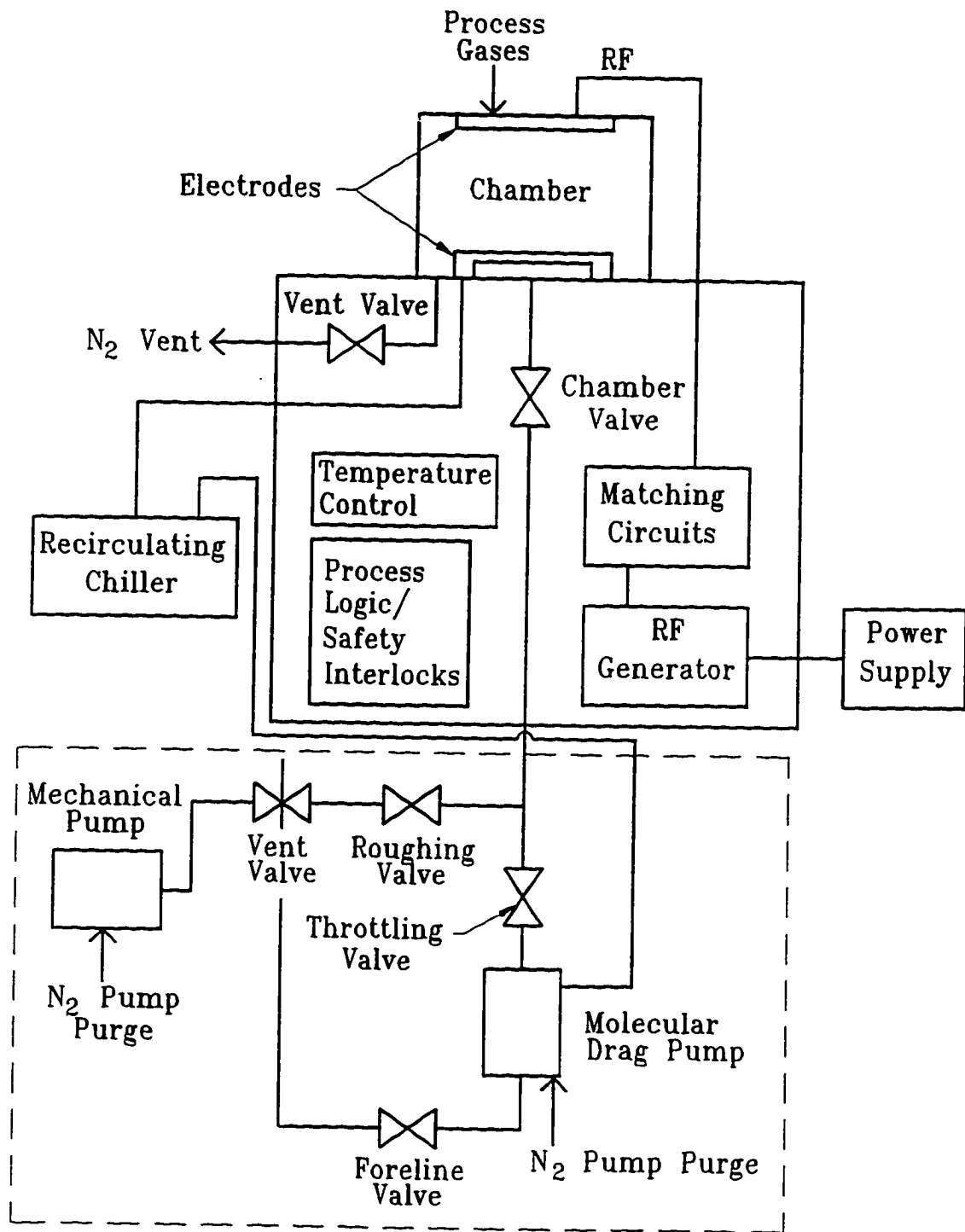


Figure 70. RIE/PECVD main system and vacuum system

the bottom plate, depending on the mode of operation. In the RIE mode, this system is used for dry etching, and the chamber is configured with the bottom electrode water cooled and used as the cathode. In PECVD mode, the system is used for deposition of silicon nitride films, and the chamber is configured with the bottom electrode heated and used as the anode, and the upper electrode cooled and used as the cathode.

The power supply provides power to the RF generator internal to the main system cabinet. Power levels of up to 200 Watts were used in various portions of the current work. The matching circuits must be adjusted for zero reverse power under each set of plasma conditions in order to avoid burning out the RF generator circuitry. Generally, a plasma should be struck without any samples in the chamber, but with all other conditions replication operating conditions to allow for fine tuning of the matching circuits. Starting at zero Watts, the forward power is gradually increased to a level below 50 Watts, and the matching circuits adjusted to provide zero Watts reverse power. The forward power level can then be increased in increments of approximately 50 Watts, adjusting the matching for 0 Watts reverse power with each increment.

Temperature control circuitry within the main system cabinet allows for the bottom electrode to be heated to a desired temperature and maintained there during the PECVD process. A resistive heater is utilized to increase the electrode temperature, and a Neslab recirculating chiller is used to help eliminate excess heat and to cool down the electrode. The recirculating chiller is left on at all times, set to 25 °C, but the compressor turns on and coolant flows only when the electrode temperature exceeds this setpoint in the RIE

mode, and when the electrode exceeds the setpoint entered into the temperature control circuitry when operating in the PECVD mode.

Process logic and safety interlock circuitry within the main system cabinet provide automatic operation of certain items. The chamber valve, for instance, is a remotely operated solenoid valve which automatically shuts when the "pump" button is turned off. The N₂ vent valve is also solenoid operated, and an interlock prevents this valve from opening when the chamber valve is open and the chamber is being pumped out. This eliminates the potential for an accidental venting of the chamber during pumping to contaminate the MDP or to trip the mechanical pump circuit breaker.

PECVD System Operation

Gas Line Purge Procedure

Prior to operating the PECVD system for film deposition, it is necessary to purge all gas lines and pump lines, to ensure the desired gases are present in the system. A full gas line purge is done before the first deposition on a given day. First, turn on the main power switch for the system if it is not already on. Check the temperature control to ensure the setpoint is below 10% so that there will be 0% power to the heater. Plug in the mechanical pump and open the mechanical pump purge line valve. Press the pump button on the front panel, and allow chamber to pump down to approximately 30 mTorr. With process gases 1 through 3 turned off at the system, the gas lines will be evacuated at least back to the mass flow controllers. Referring to the gas supply system shown in figure 68,

make sure that the emergency shutoff valve on the silane has a key inserted and turned completely counterclockwise, inactivating these valves. Shut the process valves on both the NH_3 and the silane. Open the compressed nitrogen tanks, open the high pressure valves on the N_2 lines, open the silane purge valve, and regulate the N_2 in both cabinets to approximately 45 psi.

In the silane cabinet, open the high pressure valve and the from cylinder valve. Check that the silane regulator inlet pressure is approximately 140 psi, and adjust the silane regulator to an outlet pressure of 20 psi. Open and shut the process valve briefly to fill the evacuated line with N_2 . Turn on the silane process gas using the gas 2 button on the system front panel, and flow from N_2 in the line at approximately 10 sccm on the digital meter. Monitoring the chamber pressure, rapidly open and close the mass flow controller bypass valve repeatedly and pump system to below 100 mTorr to evacuate the line, keeping pressure from increasing too rapidly. Once opening the bypass valve does not cause the pressure to jump to over 1000 mTorr, open the bypass valve. Once pressure has reached approximately 20 mTorr in the line, close the bypass valve. Repeat the process of opening and shutting the process valve briefly to fill the evacuated line with N_2 , and flowing gas 2 and rapidly opening and closing the mass flow controller bypass valve repeatedly to evacuate the line at least three times. Close purge valve on silane, leaving the N_2 at the purge valve until system operation completed for the day. Open the silane tank valve and open and shut the process valve on silane. Follow the same procedure as above to pump out the N_2 from the silane line back to the process valve. When the bypass valve can be left open, pump out the silane line back to the process valve in the gas cabinet

down to approximately 20 mTorr or below. Shut the mass flow controller bypass valve and turn off silane flow until ready for depositions. Open the silane process valve.

Due to a leak at the NH_3 cylinder valve, it is not possible to conduct a N_2 purge on the ammonia lines. After opening the NH_3 tank, the regulator inlet pressure should be approximately 150 psi. The ammonia regulator should be adjusted to an outlet pressure of approximately 14 psi. Turn on the NH_3 using the gas 3 button on the system front panel, and flow at approximately 10 sccm. Rapidly open and close the mass flow controller bypass valve repeatedly and pump system to below 100 mTorr. When the bypass valve can be left open, pump out the NH_3 line back to the process valve in the gas cabinet down to approximately 20 mTorr or below. Close the bypass valve and turn off the NH_3 flow until ready for depositions. Open the NH_3 process valve.

System Operating Procedure

The recirculating chiller should be left on with a setpoint temperature of 25 °C. Open the chamber, load samples, close the chamber and pump down using the mechanical pump. Set temperature control setpoint to about 20 °C below the desired temperature to avoid thermal overshoot. This setting will be adjusted slowly once the electrode nears the desired temperature. Turn on gas flows one at a time and dial in the desired flow rates to check settings. Leave the gases on, with the flow rates dialed to zero. Once the system has stabilized at the desired deposition temperature, open both green purge valves to turn on the MDP purges. Open the throttle valve on top of the MDP and pump out the pump down to 120 mTorr. Close the roughing valve. Open the foreline valve and pump to

below 600 mTorr. Should you need to return to rough pumping at this point, close the foreline valve and open the roughing valve. Otherwise, when the foreline pressure reaches 600 mTorr or less, turn on the turbo pump. Watch to see that the turbo gets up to speed within about 20 seconds, as indicated by a green light on the MDP controller panel turning on. Dial in the gas flows to desired levels (gases should already be turned on). Throttle MDP valve to desired pressure. Turn on the RF power supply and set the desired deposition time on the timer. When stabilized at the desired temperature and pressure, press ManRF to turn the RF power on and strike a plasma. The timer will automatically turn the RF power off when the desired deposition time is completed.

Following the deposition, turn the RF power supply off and turn off the gases. Dial in a setpoint below 20 °C on the temperature controller and verify the input drops to 0%. Close the chamber gate valve by pressing the pump switch. Close the throttle valve on the MDP and turn off the MDP controller. Allow the MDP to spin down, leaving the foreline valve open for at least 15 minutes. Close the foreline valve and the MDP purge valves and open the roughing valve, with the chamber gate valve still closed. Leave the cooling flow on and allow the system to cool down for several hours, until the temperature controller reads 90 °C or below. Open the chamber valve by pressing the pump button and mechanically pump the chamber briefly. Close the chamber valve, vent the chamber and remove the samples. If another shot is going to be done without disassembling the chamber for cleaning, the chamber can be closed, rough pumped, and cleaned with an NH₃ plasma. The chamber can also be wiped out and dried. New samples can then be loaded and the procedure described above repeated. After the last shot has

been completed for the day, the samples can be left in the system to cool overnight, or the system can be cooled and the samples removed. The entire cycle to complete a deposition takes a minimum of three hours to complete, generally longer.

System Shutdown

After all depositions have been completed, shut the process valves on the silane and NH_3 . Close the NH_3 cylinder and back the regulator off. Close the silane cylinder and back the regulator off. Close the from cylinder valves on both gases. Turn the key inserted in the emergency shutoff (overflow) valves on both NH_3 and silane completely clockwise, activating these valves for overpressure protection. Vent the high pressure gas from the silane and the NH_3 to the exhaust line by rapidly opening and closing the high pressure vent valves gently several times. Venting the silane rapidly will produce an explosion, so caution should be taken during this operation to vent the gas gradually. Close both high pressure vent valves and open both from cylinder valves. Open the process valves, flow gases and rapidly open and close the mass flow controller bypass valves repeatedly to pump out the lines back to the regulators to below 20 mTorr. Close the process valves.

Pump the chamber to below 20 mTorr. Unplug the mechanical pump and shut the mechanical pump purge valve. Open the vent valve to vent the flexible vacuum line to atmosphere. Leave the main power and recirculating chiller turned on.

Deposition Procedure

Wafer Preparation

Silicon nitride films were grown on clean Si wafers and on YZ and 128° LiNbO₃ wafers patterned with first level metal structures in this work. The Silicon wafers were delivered clean from the manufacturer, so no attempt was made to clean them further prior to film deposition. The LiNbO₃ wafers, however, often had slight levels of contamination left after the first level metal processing. In order to clean the wafers and pre-condition the chamber for film deposition, a 2 minute long ammonia plasma was struck prior to each deposition. The parameters used for this plasma cleaning were an ammonia flow of approximately 5.5 sccm, an RF power of 100 Watts, temperature of 300 °C, and pressure of approximately 250 mTorr with the plasma struck (approximately 200 mTorr without plasma).

Chamber Conditioning

PECVD is a relatively dirty process, producing film depositions not only on the wafer, but on all interior surfaces of the chamber. During Si₃N₄ depositions conducted in this work, deposits of a pink powdery substance were observed following most depositions, particularly those where a slightly elevated system base pressure indicated a slight leak and those which involved lengthy deposition times. SEM evaluation of the powder using energy dispersive X-ray spectroscopy (EDS) indicates the substance is actually a multicrystalline form of a silicon oxynitride. The presence of oxygen in this

powder explains why it was formed in greater quantities under conditions where small leaks occurred in the chamber during deposition. During some depositions, the level of production of this substance was large enough that flakes would break off of the upper electrode and the glass chamber wall and fall onto the wafers, preventing further film deposition in some spots on the wafer. While this was a nuisance, proper cleaning of the chamber prior to subsequent depositions, combined with proper attainment of vacuum seal to allow the system to reach system base pressures of 2 to 3 mTorr with leak rates of 3 mTorr/minute or less did allow for the deposition of high quality films with extremely few flaws.

Following each deposition, the chamber was disassembled, and if excessive amounts of the pink material were present, the glass chamber wall and the upper electrode were manually cleaned thoroughly using first a scrub pad, followed by methanol on cleanroom wipes. The chamber was then wiped out with DI H₂O on cleanroom wipes and dried with N₂. Periodically, after every few depositions, the chamber was cleaned as described above, then evacuated and cleaned using a C₂F₆ plasma at 150 Watts, 210 mTorr, 40 °C, and a C₂F₆ flow rate of 10 sccm as measured on the digital meter for gas 1. These plasma cleaning processes were run for anywhere from 5 minutes to two hours in an attempt to clean the chamber. Because Si₃N₄ is etched by C₂F₆ plasmas, this cleaning process should have removed any silicon nitride films deposited on the chamber walls. However, observations of polymer-like films being deposited on the surface of LiNbO₃ die during O₂ plasma cleaning processes later raised the question of whether this C₂F₆ plasma process actually removed the Si₃N₄ films, or rather led to the deposition of some type of

fluorocarbon film inside the chamber instead. This issue has not been resolved, but film deposition was avoided by maintaining RF power at or below 100 Watts during oxygen plasma cleaning.

Film Deposition Conditions

The deposition conditions described as optimal in Chapter 2 were utilized for most of the depositions used in the current work. The system operation is described in detail above. Additional details of the deposition technique can be found in [33-36].

The Wafers were loaded into and later removed from the chamber at temperatures not exceeding 90 °C, to avoid excessive thermal shock. Delamination of the Si_3N_4 films from the wafers was observed when the wafers were cooled too rapidly. To avoid this effect, trays were preheated to approximately the temperature at which the wafers would be removed from the PECVD system. The warm wafers were then removed onto these trays and allowed to cool gradually. There was no problem in loading room temperature wafers without Si_3N_4 films directly onto the PECVD system electrode at temperatures of up to 90°C. Once new wafers had been loaded and the chamber was closed and being rough pumped, the substrate temperature was ramped up to 300 °C for the depositions, and was generally held within ± 2 °C for the entire deposition procedure.

Once the system was under vacuum, the mechanical pump was usually allowed to pump down for approximately 2 hours, achieving a base system pressure of roughly 2 mTorr. This extended pumping time was intended to help ensure that most adherents to the chamber walls and fixtures had been removed prior to deposition, and allowed time for

the substrate to stabilize at the desired process temperature. The leak rate was checked at this point, and if it exceeded approximately 5 mTorr/minute, the system was cooled down, opened, re-cleaned, and the process was started over. Although this led to substantial delays in the film deposition process, it was necessary to ensure high quality films.

Once the system stabilized at a favorable base pressure and at the deposition temperature, and the MDP and lines had been pumped out, the MDP was turned on and observed to ensure it came up to speed. The ammonia flow was then turned on and dialed up to approximately 5.8 sccm on the digital meter for gas 3, and the silane flow was turned on and dialed up to approximately 51 sccm on the meter for gas 2. These values actually represent a SiH_4/NH_3 flow ratio of 0.705, due to the use of a mass flow controller calibrated for 100% silane flow, and a process gas consisting of 3% SiH_4 in He. The system pressure is throttled to 700 ± 5 mTorr using the MDP inlet valve prior to striking the plasma, and is maintained at this level by adjusting the throttle valve during the deposition process.

All depositions were conducted with a forward RF power of 100 Watts, with the reverse RF power tuned to virtually zero.

System Conversion

The system can be converted from RIE to PECVD and vice versa.. It takes an experienced individual approximately four hours to complete the conversion, and an additional four to eight hours to troubleshoot and test the system. The procedure below is for conversion from RIE to PECVD, although the reverse can also be done.

1. Turn the main power on, vent the chamber and open it fully. Turn the main power off.
2. Remove the two rubber covers and the screws that hold the top shield in place, remove the shield.
3. Undo all screws holding the outer Plexiglas ring in place, lower ring.
4. Undo the one screw on the metal band holding the inner glass chamber wall.
5. Holding the outer ring up and using your fingertips, rotate the inner glass chamber wall until it is freed. Carefully remove both the glass wall and the outer ring simultaneously.
6. Close the supply line valves on the two water lines. Hook up the N₂ from above the vacuum system to the T on the top water line and remove the cap from the upper overflow point. Using a beaker to catch the ethylene glycol, blow out the line. Repeat for the second line. Pour the coolant into the chiller reservoir. Turn on the recirculator to pump down the line. Place a stopper in the pipe and tape it to prevent leaks. Clean up any spills or leaks and change gloves prior to continuing with the conversion process.

7. Pull out the main drawer and rest it on a tall bench, being careful not to snag water lines and cables and to not put too much tension on the back cables.
8. Turn the three casings to reveal the underworks (two water and one RF).
9. Disconnect the RF cable at the quick connect and slide down.
10. Undo the water lines at the upper fitting and pull off, removing from the back attachment using a wrench. Remove the water lines and blow out into the trash using N₂. Set aside to dry.
11. Remove the RF line.
12. Remove the ground shield (held by two screws).
13. Remove the ground post by loosening the vacuum seal with a wrench, backing off the screw, and repeating this process.
14. Cap the ground hole with a nut cap.
15. Remove the four black vacuum seal rings, being sure to remove the inner fitting and O-ring for each.
16. Remove lower electrode.
17. Remove the two diagonal Teflon inserts with small holes and replace with inserts with larger holes. Be careful not to cross-thread inserts.
18. Insert lower electrode with white spacers. Tighten bolts on Teflon inserts.
19. Re-grease and install four O-rings. Install black tightening rings.
20. Place glass chamber wall on O-ring. Turn main power on, close chamber, pump down to about 20 mTorr, and check for leaks. If system is not leaking, turn the pump off, vent system, open chamber and remove the glass chamber wall. Turn

- the main power off and continue with conversion procedure. If the system is found to be leaking excessively, troubleshoot prior to continuing the conversion.
21. Install four brass waterline pieces with the flat side toward the inside and top, tighten the Allen bolts.
 22. Reattach to the two water supply lines and open the water line supply valves. Turn on the circulator to check for leaks. If no leaks are found, turn the circulator off and continue with conversion. If leaks are present, fix the leaks prior to continuing with the conversion.
 23. Connect the ground strap to the back ground bar and the back ground leg of the electrode. Wiggle the shield up onto the O-ring.
 24. Connect the RF cable to the source (at the back) and to the top plate using feedthroughs that are insulated. Remove the ground straps from the top plate and be sure they do not touch the plate or the RF cable.
 25. Connect the heater element to two legs of the electrode with washers and nuts. Slide the shields up.
 26. Plug in the power to and from the heater source.
 27. Insert thermocouple into electrode leg and plug into monitoring box.
 28. Slide the main drawer in, making sure no water lines or cables get caught or pinched.
 29. Turn the main power on. Check the temperature control to verify the setpoint is 10% or lower and 0% power output. This ensures the electrode will not heat up during the system verification process.

30. Check the movement of cables when opening and closing the chamber.
31. Re-install the inner glass wall and outer chamber shield. Pump down the system to check vacuum. Vent the system and proceed.
32. Install the cover.
33. Draw a vacuum. Strike a plasma to verify there are no shorts in the system.
34. System is ready to be configured for a test run of the desired PECVD process.

APPENDIX D

ELECTRON BEAM EVAPORATION SYSTEM AND PROCEDURE

ELECTRON BEAM EVAPORATION SYSTEM AND PROCEDURE

Evaporation of Aluminum films used as the top level metallization in the multilevel transducer structures described in Chapter 1 was performed using an electron beam (e-beam) evaporation system at the Solid State Devices and Systems Laboratory (SSDSL) of UCF.

System Description

Electron beam evaporation is a process which occurs when directing a high-intensity beam of electrons onto a target containing the material to be evaporated. The kinetic energy of the electrons is converted into heat and atomic excitation energy, which causes the target material to melt and evaporate. Since this process occurs in vacuum conditions, the evaporation results in deposition of a film of essentially the same composition as the target on exposed substrates.

The evaporation system consists of an e-beam gun assembly, a high voltage power supply for the e-beam gun, and a vacuum system, as shown schematically in Figure 71. Electrons are emitted from an incandescent cathode filament in the presence of a strong electric field between the cathode and anode. The electrons are accelerated by the electric field, and the beam is shaped by the anode geometry. The electron beam is then bent,

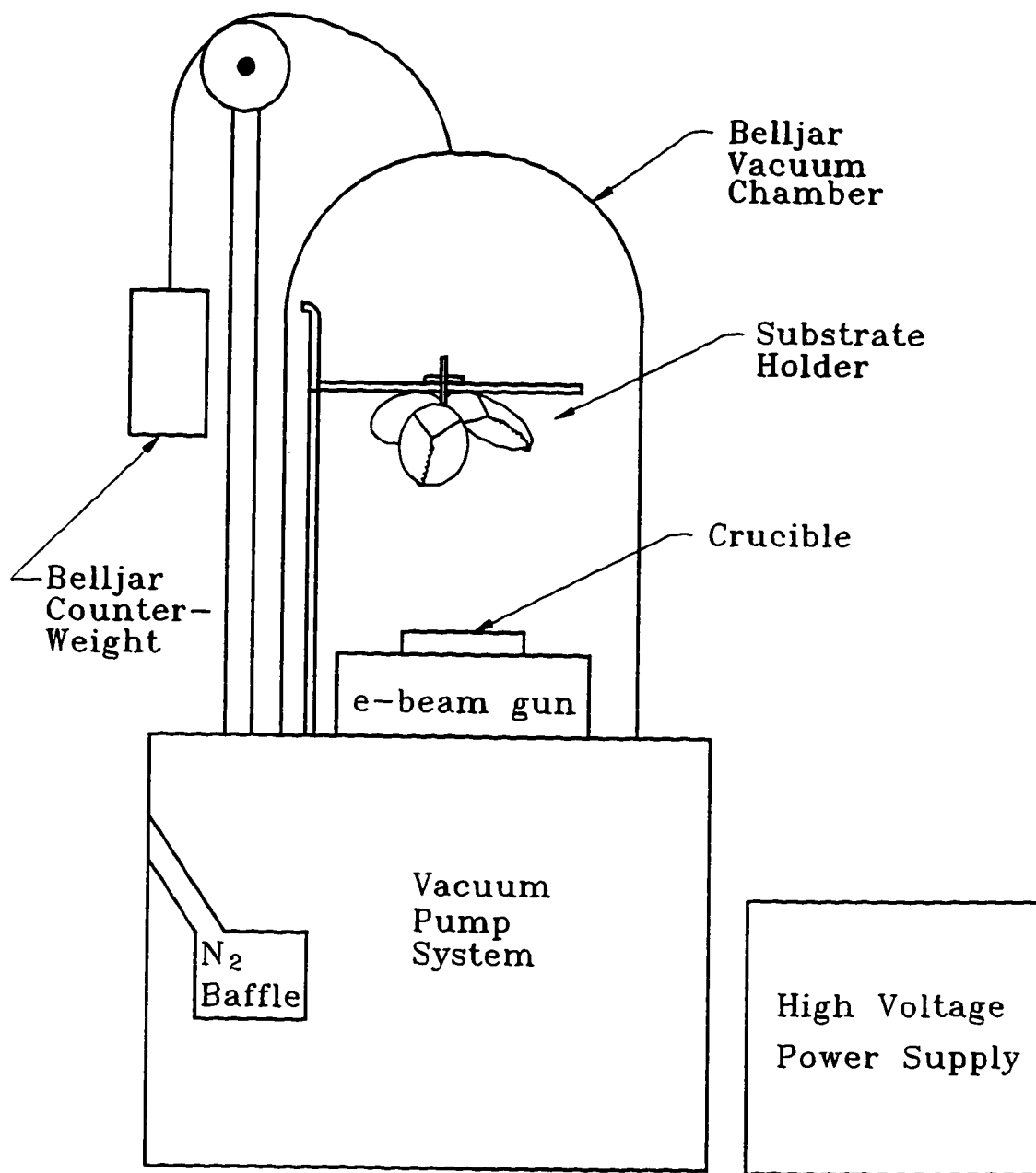


Figure 71. Electron beam evaporation system block diagram.

which leads to impact of the beam on the target, by a magnetic field generated by permanent magnets installed in the system. Portions of the magnets can be adjusted to

focus the beam spot. Electromagnets within the e-beam gun can be used to position the beam spot longitudinally and transversely, and provide control of the beam sweep across the target material during the evaporation process.

A constant voltage, 4 kWatt power supply is used to provide power and control of the e-beam gun. The power supply used in this work can supply up to 10.2 kV at 0.4 A to the e-beam gun, while providing power to the filament. The high voltage can be adjusted and maintained at the desired value to within $\pm 2\%$.

The e-beam gun assembly is mounted on the stainless steel base plate of a vacuum chamber. In addition to a large bell jar vacuum chamber, this vacuum system is equipped with a mechanical rough vacuum pump, a high vacuum diffusion pump, and a liquid nitrogen baffle. Foreline and chamber pressures are monitored using thermocouple sensors and monitored using a dual meter. High vacuum pressures are monitored using an ionization gauge glass tube with a meter controller. Further details on the system design and installation can be found in [77].

System Operation

Material Loading

The e-beam gun used in this work has a four pocket crucible with a rotating turret for target selection. Each pocket of the crucible holds up to 7 cm³ of evaporant material. The crucible pocket utilized as a target for evaporations in this work contains an aluminum target. As material from the target is consumed, additional aluminum can be added in the

form of small pieces of aluminum wire, by placing the pieces in the crucible pocket, being sure they do not extend beyond the rim.

Substrate loading

One to three lithium niobate wafers with three inch diameters were loaded onto a planetary substrate holder prior to film deposition. Silicon wafers were used for test depositions. Each wafer was held in place from the back by a spring loaded clip, and the entire planetary assembly is placed into the opened vacuum chamber, suspended approximately 8 inches above the crucible containing the target material.

Pumpdown Sequence

After closing the chamber, the mechanical roughing pump is turned on using the switch on the control panel. The chamber valve on the front panel of the vacuum system frame is opened and the bell jar is pumped down to 20 mTorr.

Once the chamber pressure is below 20 mTorr, the chamber valve is closed and the foreline valve is opened, pumping out the diffusion pump to 20 mTorr or less. The water line valves to the electron beam gun and the diffusion pump are opened, and the diffusion pump is turned on using the switch on the control panel. The diffusion pump is allowed to warm up for 30 minutes, and the liquid nitrogen baffle is then filled. Since the chamber has slight leaks and outgassing has continued to some extent, the chamber pressure may have increased following closure of the chamber valve. Before the chamber is exposed to the high vacuum diffusion pump, the foreline valve must be closed and the chamber valve

opened to reduce the chamber pressure to below 20 mTorr. During this process, the foreline pressure is monitored on the thermocouple gauge, and should remain below 60 mTorr. If the foreline pressure increases above 60 mTorr, close the chamber valve and open the foreline valve to reduce foreline pressure. This process can be repeated until the desired pressures are achieved. Once the chamber pressure is achieved with the chamber valve closed and the foreline valve open, the high vacuum valve is slowly opened to full throttle. The chamber is pumped until the deposition pressure is achieved. For the aluminum depositions used in this work, a deposition pressure of 10^{-5} Torr was used.

Evaporation

Once the chamber has reached the desired pressure for deposition, the SR4A power supply main switch is turned on. The high voltage at the control module is turned on using a key and switch sequence. Checking to verify that the high voltage knob is turned completely counterclockwise, the high voltage knob is slowly turned clockwise to achieve a voltage of 7.9 kV. The emitter knob is then turned completely counterclockwise, and the emitter switch is turned on, which starts the filament glowing. The emitter knob is turned clockwise slowly to achieve a current of 0.35 amps. Once the beam is established, the shutter is removed and the evaporation is conducted for the desired time. Aluminum film deposition is monitored using an in-line crystal deposition monitor. At 7.9 kV and 0.35 A, the deposition rate of aluminum is approximately 14 Å/sec, while at 7.8 kV and 0.3 A, a rate of 10 Å/sec is observed.

System Standby

Once the desired evaporation has been completed, the shutter is positioned to prevent further deposition, and the emitter current is lowered slowly by turning the emitter knob slowly counterclockwise. Once the emitter knob is completely counterclockwise, the emitter current is turned off using the control module switch. The high voltage knob should then be turned completely counterclockwise, and the high voltage is switched off and disabled by turning the key. The power supply module should be left on for at least 5 minutes to cool. The heater Variac is then turned to 0% and switched off, and the high vacuum valve is slowly shut tightly. The chamber is vented with nitrogen from the valve on the front panel. The counterbalance is placed on the bell jar pulley drive and the bell jar is slowly lifted to its highest level. Make sure the power supply module is turned off, and as a precaution to avoid high voltage contact, short the secondary filament transformer connections with the ground hook located behind the power supply module. The planetary substrate holder is removed from the chamber and the substrates are carefully removed. Close the chamber and remove the counterbalance. Close the foreline while monitoring the foreline pressure and open the chamber vacuum valve to pump the chamber to 50 mTorr or less. Close the chamber vacuum valve and open the foreline valve for standby mode.

System Shutdown

Turn off the diffusion pump at the switch panel and allow the pump to cool for at least 30 minutes before closing the foreline and water valves. After the e-beam gun has

cooled for 30 minutes or more, close the water line valve to the gun. After proper cooling of the system, close the foreline valve then turn off the mechanical pump using the panel switch. Before leaving the system, make the following checks:

1. All red light indicators on the switch panel are off.
2. Water to the gun and diffusion pump are off.
3. Vacuum gauge meter switch is off.
4. Thermocouple thermometer is off.
5. Heater switch and Variac are off.
6. SR4A main switch is off.

Deposition Rate

Several test evaporations were conducted to determine the deposition rate, and to evaluate the metal uniformity across three wafers onto which Al was evaporated simultaneously. Film deposition was monitored real-time using an in-line monitor that provided a digital readout proportional to the thickness of the film deposited.

The measured deposition rate with the conditions described above was approximately 14 Å/sec. Based on test runs, it was determined that in order to achieve the film thickness desired, a meter reading of 0.88 times the actual desired film thickness must be obtained. This value has been verified for Al films ranging from roughly 900 Å to roughly 1500 Å.

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