MULTI-PIEZO FILM MICROWAVE ACOUSTIC TRANSDUCERS*

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Abstract

High performance bulk-wave transducers employing alternating half-wavelength thick piezoelectric and acoustically matched metal films have been fabricated to operate in Ku-band. Longitudinal-mode transducers employing zinc oxide and copper films fabricated on sapphire substrates yielded an untuned conversion loss of 25 dB from 8 to above 14 GHz.

Introduction

Conventional microwave acoustic transducers have usually employed a three-film configuration consisting of a piezoelectric film bounded by acoustically thin metal electrode films.[1] Scaling this design to frequencies above 5 GHz becomes difficult because the metal electrode films become unreasonably thin.[2] Also, the top contact area corresponding to a reasonable capacitive reactance (i.e., above 10 ohms) becomes inconveniently small. We have found that a modification of the muiti-piezo film configuration introduced in 1965 by deKlerk, et al,[3] can reduce these problems. The multi-piezo film design utilizes an alternating stack of N half wavelength thick piezoelectric and passive films as shown in Fig.1. The passive films may be either dielectric or metal.

The devices described here employed Cu and ZnO films because our analysis indicated that their closely matched acoustic impedances provide minimum transducer conversion loss with large bandwidth. Also, the technology for ZnO and Cu film fabrication using rf sputtering techniques[4] is sufficiently mature that high quality films are reproducibly available.

The improved operating characteristics of multi-piezo film transducers results from the in-phase addition of the strains generated in the N piezo films at the design frequency f_o. Consequently, the transducer radiation resistance is increased by N^2, and the input capacitive reactance increases as N. Compared to the conventional design, the multi-piezo film transducer has lower conversion loss, larger top electrode diameter, and higher input power capability. These benefits are gained at the expense of reduced acoustic bandwidth. However, theory and experiment show that designs up to N = 3 can provide a 3 dB bandwidth of 30 percent and larger.

Analysis of Operation

Ideal Transducers

The qualitative properties of multi-piezo film transducers may be understood from analysis of an ideal transducer structure which has uniform acoustic impedance and has film thicknesses chosen to be one-half wavelength thick at the design frequency f_o. With reference to Fig.1 and using the notation of Ref.1, these conditions correspond to $Z_m' = Z_p' = Z_D'$ and $f_o = v_m/2\,t_m = v_p/2t_p$. Following Tehon and Wanuga,[5] the one-dimensional thickness mode vibrations of the N piezo films can be summed at the acoustic substrate surface to obtain the frequency dependent stress response of the ideal transducer. The boundary condition at the top electrode surface where the bonded wire top contact is made significantly affects the results.[2] For an acoustically free (reflecting) top contact, the acoustic stress at the substrate is approximately

$$T_r(f) \simeq 2NT_o \frac{\sin 2N\pi(f - f_o)/f_o}{2N\pi(f - f_o)/f_o}$$

The constant T_o is proportional to both the electromechanical coupling constant k and the applied electric field. On the other hand, for an acoustically matched (absorbing) top contact, the stress response becomes

$$T_a(f) \simeq NT_o \frac{\sin N\pi(f - f_o)/f_o}{N\pi(f - f_o)/f_o}$$

As could be expected by analogy with interdigital surface wave transducers,[6] the stress output of the ideal multi-piezo film transducer has a sinX/X type of response. In comparison with the absorbing contact case, the reflecting contact structure has twice as much stress output and its frequency response varies twice as fast. Since the zeros and peaks of the stress output become poles and minima in the transducer conversion loss response, the conversion loss response provides a signature which is determined by both the number of active piezo-films and the absorptivity of the top contact.

Nonideal Transducers

In the general case where the film and substrate acoustic impedances are not equal and the film thicknesses are arbitrary, the transducer impedance and conversion loss characteristics can be found from equivalent circuit models. The equivalent circuit in Fig.2 provides an exact model for lossless N piezo-film transducers that can be described by single mode, one-dimensional vibrations. Following Krimholtz, et al,[7] each piezo-film is represented by an acoustic transmission line with phase angle θ_{pi} and equivalent electrical impedance R_{pi}, a frequency dependent transformer with turns ratio ϕ_{ai}, a reactance X_{ai}, and a series capacitance C_{oi}. The metal films, which in experimental devices often consist of a composite of two or

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more layers, are represented by acoustic transmission lines with phase angle θ_{mj} and equivalent resistance R_{mj}. The top contact and acoustic substrate loads are represented by equivalent resistances R_B and R_D.

We have used the circuit in Fig.2 as the basis for a computer program which computes the transducer input impedance, conversion loss, and transfer phase as a function of frequency. The program includes the effect of external elements used in some cases to electrically "tune" the transducer. In order to compare the results obtained with this program against the simple ideal transducer analysis discussed earlier, we show in Fig.3 a series of conversion loss curves computed for ideal transducers with a reflecting top contact surface ($R_B = 0$) and N = 1, 2, and 3. The transducer constants assumed in these calculations were $k^2 = 0.04$, $C_o = 4$ pF and $f_o = 10$ GHz which corresponds to ZnO piezo-film devices with 0.125 mm top electrode diameter. Untuned operation from a 50 ohm source was assumed. The curves in Fig.3 clearly demonstrate the expected response due to the sinX/X stress variation. Note that if the top contact were absorbing, the conversion loss poles nearest f_o would be absent. The 3 dB bandwidth is approximately doubled with the absorbing top contact, but the conversion loss is increased by about 6 dB. Table I compares the design tradeoffs available for reflecting and absorbing top contact transducers with the chosen parameters.

Calculations for the general case where the film and substrate acoustic impedances are not equal shows that ripples are introduced into the conversion loss passbands. However, by careful choice of the film impedances and thicknesses, a desired passband can be optimized to give, for example, an equi-ripple response. This flexibility in passband response is not available in conventional transducers, and with development, could be used for transducer applications requiring prescribed passband synthesis.

Fabrication and Experimental Results

The Ku-band transducers were fabricated on c-axis Al_2O_3 substrates with parallel ends and a round trip delay of 1 μsec. Devices with N = 2 and 3 were fabricated with f_o in the 14 to 15 GHz range using rf sputtered ZnO piezo films. The ZnO was deposited on rf sputtered Cu which has an acoustic impedance close to ZnO. A 500Å film of Cr was used to adhere the Cu to the ZnO and the Al_2O_3. Another 500 Å rf sputtered Al film was employed on the top contact surface to assist in bonding to the 0.025 mm dia. Al bonding wire.

The delay lines were mounted as a termination to a 50 Ω microstrip line. This allowed input impedance measurements with the reference plane at the transducer. The external circuit was modeled using a series inductance (typically 0.6 nH), and a series resistance (typically 5 ohms) in series with the transducer. The devices reported here were operated untuned, i.e., directly from a 50 ohm source. Pulse-echo techniques were used to study the insertion loss over the 1 to 14 GHz range. The delay line mount was constructed to allow optical probing of the acoustic beam to obtain an independent measure of the Al_2O_3 propagation loss.

The pulse-echo insertion loss measurements for an N = 2 device with 1 μsec round trip delay are shown in Fig.4. The pole near 7.5 GHz clearly indicates the presence of two piezoelectric films, and the lack of a large pole near 11 GHz indicates that the top contact and bonding lead are nearly perfectly absorbing. The theory curve in Fig.4 was obtained as a best fit to the experimental data using bulk values for the acoustic impedances, the measured film thicknesses, measured transducer capacitance at 1 MHz, and varying the k^2 and the substrate propagation loss parameters. Propagation loss in the Al_2O_3 substrate was assumed to vary as[8]

$$PL = A[f(GHz)/10]^2 \text{ dB}/\mu s ,$$

and diffraction loss, which became important at frequencies below 6 GHz for the 0.125 mm top electrode diameter employed here, was included in the theory using the approach described by Papadakis.[9,10] The theory experiment comparison in Fig.4 was obtained for $k^2 = 0.06$ and A = 22 dB/μs, values considered typical for ZnO films and c-axis Al_2O_3 substrates.

The computer generated one-way conversion loss curve corresponding to the theory curve in Fig.4 is shown in Fig.5. Note that the major passband extends from 8 GHz to almost 22 GHz. Although the plot shown here extends only over the experimental measurement range which ended at 15 GHz, the computed conversion loss is predicted to be 25 ± 5 dB from 8 to 20 GHz.

Conclusions

Multi-piezo film transducers give reduced conversion loss, increased input impedance for given transducer area and higher breakdown voltage compared to a single piezo film transducer. Utilizing ZnO piezo films in the N = 2 configuration, microwave transducers with 25 dB conversion loss in Ku-band have been fabricated.

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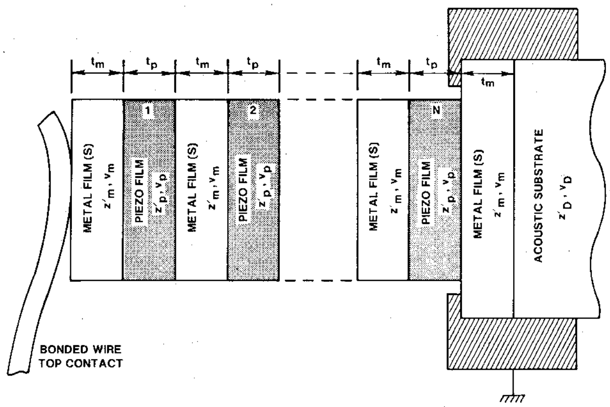

Fig.1 The physical configuration of a multi-piezo film transducer.

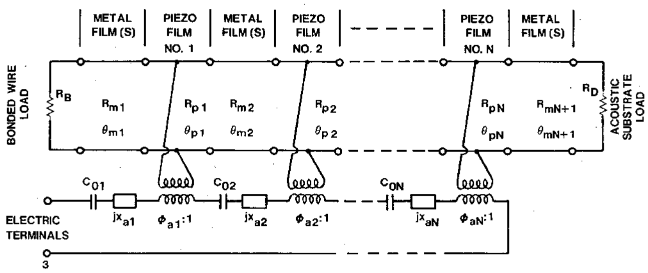

Fig.2 The electrical equivalent circuit used to model the performance of a multi-piezo transducer.

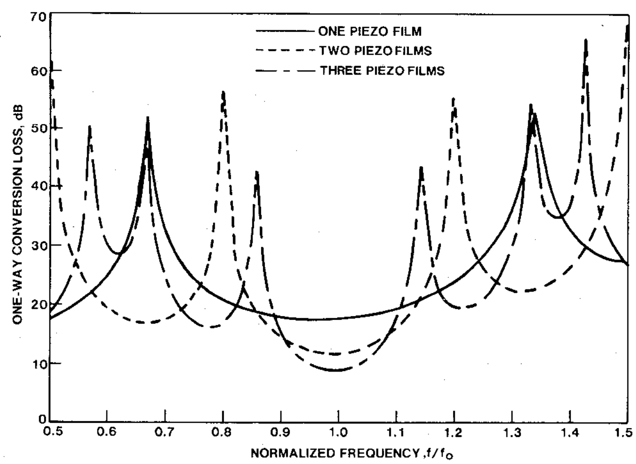

Fig.3 The one-way conversion loss versus frequency for an ideal transducer as a function of the number of piezo films.

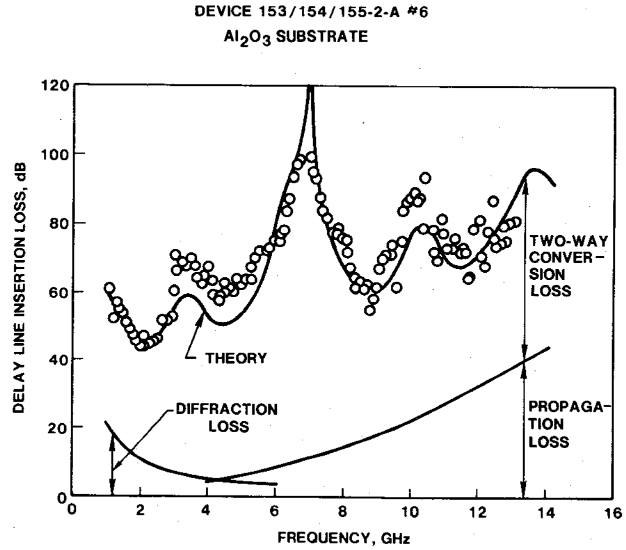

Fig.4 The untuned experimental and theoretical round trip insertion loss of a 1 μsec Al_2O_3 delay line and a 15 GHz transducer with two ZnO films. The diffraction and propagation loss contributions are indicated.

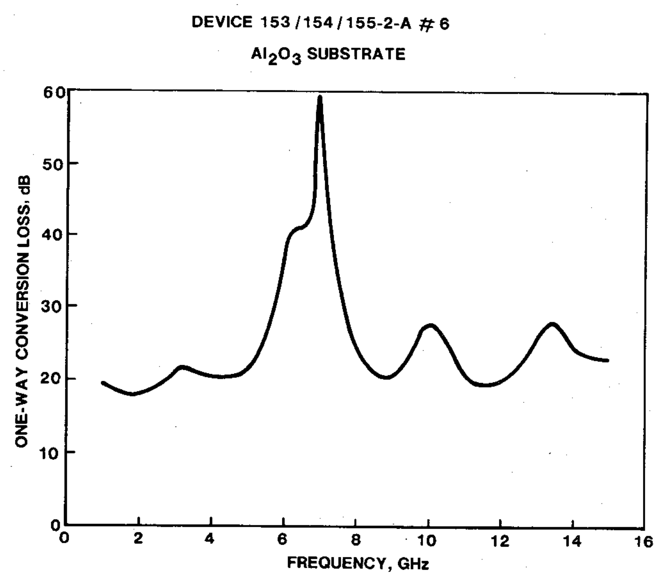

Fig. 5 The one-way untuned transducer conversion loss versus frequency computed from the theoretical curve in Fig.4.

TABLE I

Minimum Conversion Loss and Bandwidth for an Untuned Ideal Transducer
(Transducer Parameters: f_o = 10 GHz, k^2 = 0.04,
C_{oi} = 4 pF, and source impedance = 50 Ω)

	Reflecting Top Contact		Absorbing Top Contact	
Number of Piezo Films	Conversion Loss @ f/f_o	3 dB Bandwidth	Conversion Loss @ f/f_o	3 dB Bandwidth
1	18 dB @ 0.96	30%	21 dB @ 0.3	Large
2	12 dB @ 0.99	18%	18 dB @ 0.91	45%
3	9 dB @ 1.0	14%	15 dB @ 1.0	30%