Fabrication of 945 MHz Band Film Surface Acoustic Wave Resonators Using ZnO Thin Film with Si Substrate

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***Abstract*—This paper, we present the analysis of a ladder-type filter, in the frequency band of 945MHz, developed on a structure with two layers of a ZnO film on a Silicon substrate with aluminum (Al) IDTs using coupling of modes (COM) theory. The case of a layer ZnO deposited on a not-piezoelectric substrate, [111]-[110]-Si is examined. Although silicon is no piezoelectric, the configuration gives for the modes of surface of a higher order, the coupling coefficients K2 of about 5.5% (quite higher than the maximum value obtained for ZnO alone 1%) with the metallization coefficient of 0.5. We presents the optimization of the characteristics SAW, in particular by the choice of:-the thickness of the piezoelectric layer,-localization of IDTs,-the metallization or not of surface or interface,-crystalline orientation of the substrate and propagation direction, - the thickness of the fingers of IDT. The transfer function of SAW ladder type filter resonators (6 resonators) is presented, analyzed and compared with the experimental results. This frequency response confirms that it is possible to integrate on Si substrate the filters use for GSM and DECT systems.**

I. INTRODUCTION

Recent developments in personal communications systems have underlined the need for RF filters that exhibit the following characteristics: small size, ruggedness, reproducibility, reliability, power efficiency, and high production volume at a low cost. The frequency response of the Surface-acoustic-wave (SAW) devices is in the 40 MHz to 3 GHz range, which makes them suitable for cellular telephones and satellite communication systems. A new class of SAW filters is being developed which is based on the use of one port SAW devices as building blocks connected electrically in networks of ladder type [1,2], balanced bridge scheme, etc. There are experimental as well as theoretical investigations on layered SAW filters with ZnO on a GaAs substrate [3]. Visser [4] presents the SAW resonator of intermediate frequency of 160 MHz based in a ZnO-SiO_2-Si structure.

We first describe the coupling of modes (COM) model approach used for analysis of one port SAW resonator. Compared with other models for the design and analysis of SAW devices, the coupling of modes (COM) model provides an efficient and highly flexible approach for modeling various types of electrodes, and has been used widely in modeling no dispersive SAW devices for many years [5]. Parameters of the COM differential equations are usually obtained by measurements or by borrowing from same related theoretical modeling [6]. Recently, some precise numerical tools to analyze SAW properties, and further, calculate the COM parameters have been proposed [7].

II. COM MODEL FOR A SAW FILTER

Consider the single – electrode IDT with periodicity 2p , a length L and N pairs of electrodes as shown in Fig.1.

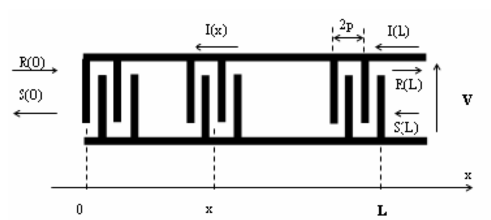


Fig.1: IDT structure.

The origin of the x axis is at the centre of the electrode at the left end. If we denote the particle velocities of the forward going and backward going surface acoustic waves by R(x) and S(x) , respectively, the differential equations on the mode amplitudes R(x) , S(x), the voltage V, and the bus bar current I(x) can be expressed as follows [8]:

$$\frac{dR(x)}{dx} = -j\beta R(x) - j\kappa S(x) + j\varsigma V \quad (2a)$$

$$\frac{dS(x)}{dx} = j\kappa^* R(x) + j\beta S(x) - j\varsigma^* V \quad (2b)$$

$$\frac{dI(x)}{dx} = -2j\zeta^* R(x) - j2\zeta S(x) + j\omega C_s V \qquad (2c)$$

where:
$R(x), S(x)$ = The slowly varying amplitudes of the forward and backward waves respectively,
k_{11} , κ = coupling coefficients,
V and I are applied voltage and current drawn by the IDT. $\beta = (\omega - \omega_0)/v_f + k_{11} \cong k_f - k_0$ (wave mismatch).
$k_f = \omega / v_f$ (the free wave vector),
$k_0 = 2\pi / \Delta_t$ (Δ_t=2p is show in fig 1).

ω , C_s and ς are respectively the radian frequency, the static capacitance per unit length and with of the transducer and the transduction coefficient.

A. The COM Parameters k_{11} and κ

The parameters k_{11} and κ are closely related to the more commonly used parameters of average velocity shift $\Delta v / v_f$ and acoustic mismatch $\Delta Z / \Delta Z_0$ respectively [9]. These relationships were derived [10]:

$$k_{11} / k_f = -(\Delta v / v_f) \qquad (3a)$$

$$\kappa / k_f = -(1/\pi)(\Delta Z / Z_O) \qquad (3b)$$

$$\frac{\Delta v}{v_f} = D_k \left(\frac{k^2}{2} \right) + D_m \left(\frac{H_m}{\lambda} \right) \qquad (3c)$$

$$\Delta Z / Z_O = R_k (k^2/2) + R_m (H_m / \lambda) \qquad (3d)$$

where k^2 is the electromechanical coupling coefficient, H_m is the metal film thickness and λ is the acoustic wavelength. The first terms on the right side of both (3c) and (3d) represent the piezoelectric loading effect, and the two right most terms represent the mechanical loading effect.

B. The Electrical and Mechanical Perturbation Terms

The electrical perturbation terms D_k and R_k can be written as

$$D_k = -\frac{1}{2}\left[1 + \frac{P_{0.5}(-\cos(\pi\eta))}{P_{-0.5}(-\cos(\pi\eta))}\right] \qquad (4a)$$

$$R_k = -\frac{\pi}{2}\left[\cos(\pi\eta) + \frac{P_{0.5}(-\cos(\pi\eta))}{P_{-0.5}(-\cos(\pi\eta))}\right] \qquad (4b)$$

where $P_v(x)$ is the Legendre function of order v and η is the metallization ratio (see B.11 and B.14 in [9]).
The mechanical perturbation terms are [9]

$$D_m = \frac{\eta\pi k^2}{C_s}\left[\left|\frac{U_1}{\varphi}\right|^2 (\alpha_1 - \rho v_f^2) + \left|\frac{U_2}{\varphi}\right|^2 (\alpha_2 - \rho v_f^2) - \left|\frac{U_3}{\varphi}\right|^2 \varphi v_f^2\right] \qquad (5a)$$

$$R_m = -\frac{\pi k^2}{C_s}\left[\left(\frac{U_1}{\varphi}\right)^2 (\alpha_1 + \rho v_f^2) + \left(\frac{U_2}{\varphi}\right)^2 (\alpha_2 + \rho v_f^2) + \left(\frac{U_3}{\varphi}\right)\rho v_f^2\right] \qquad (5b)$$

where ρ is mass density, α_1 and α_2 characterize the overlay material. U_i and φ represent magnitude and phase of the free surface mechanical displacements and electrical potential [9].
We can replace $U_1/\varphi = c_X, U_2/\varphi = c_Y, U_3/\varphi = c_Z$; where $c_{x,y,z}$ are properties of the layer material (c_x = 0 in our case), ρ is the density and α_x, α_y, α_z describe properties of the electrode material.
For aluminium reflectors α_x = 2.5 10^{10}N/m^2, α_z =7.8 10^{10}N/m^2 and ρ = 2695 kg/m^3.
Fig.2 shows the calculated c_y and c_z of the ZnO/Si analyzed structure against normalized thickness.

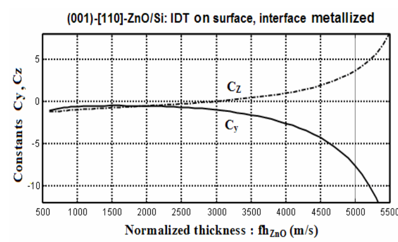


Fig.2. Constants c_y and c_z.

The coupling coefficient κ depends on the squared phase velocity. We note that the displacements, the surface electrical potential and the electromechanical coupling coefficient of the surface wave are frequency dependent in a ZnO/Si SAW structure.
The transduction coefficient ζ which is responsible for the excitation efficiency of the IDT can be derived as [8]:

$$\zeta_p = \sqrt{\frac{\omega\, Cp\, K^2}{\pi}} \qquad (6)$$

where Cp is the static capacitance per IDT finger pair given by [13],

$$Cp = \left(\varepsilon_0 + \sqrt{\varepsilon_{11}^T \varepsilon_{33}^T - \varepsilon_{13}^{T2}}\right)\frac{K[\sin(\eta\pi/2)]}{K[\cos(\eta\pi/2)]} \qquad (7)$$

where η is the finger width to grating period ratio, $\eta = a/p$, and K(x) is the complete elliptic integral of the first kind .
Owing to the dispersive nature of the M_1 mode, the transduction coefficient which depends on the square root of ω times the electromechanical coupling coefficient K^2 is a quite complicated function of the frequency.

For a dispersive layered SAW filter, some of the COM parameters become frequency dependent due to the phase velocity dispersion [11]. The effective permittivity of a layered piezoelectric structure [12] was used to calculate the velocity and the electromechanical coupling coefficient (Fig.3.).

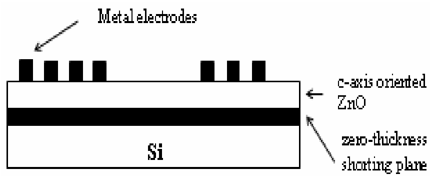


Figure 3. Schematic of IDT/ZnO/Si structure.

Shown in Fig.4. is the calculated phase velocity dispersion of the first five SAW modes M_0 to M_4 of the ZnO/Si structure with the shorting plane at the ZnO and Si interface . The horizontal axis is the frequency - ZnO layer thickness product fh_{ZnO}. ZnO is the single piezoelectric material which has been successfully fabricated on a Si substrate as a film and has shown an excellent piezoelectricity.

The electromechanical coupling coefficient K^2 of a piezoelectric medium can be approximated as [13]:

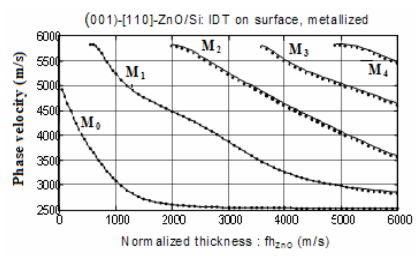


Fig.4: Phase velocity of ZnO/Si structure.

$$K^2 = 2\ \frac{v_0 - v_m}{v_0} \qquad (8)$$

where v_m is the surface wave velocity with metallized surface and v_0 is the free surface wave velocity defined as before. Fig.5 shows the calculated electromechanical coupling coefficients for the five SAW modes. We used the second mode M_1 which goes to a maximum 5.8 %, and for which the phase velocity is presented in Fig.4.

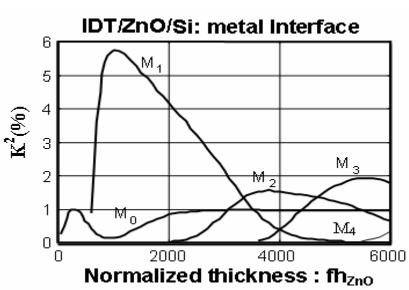


Figure 5. Electromechanical coupling coefficient.

C. *Transmission Matrix of IDT and Grating*

Let us represent an elementary cell of IDT formed by the pair of interdigitated electrodes shown in Fig.6,

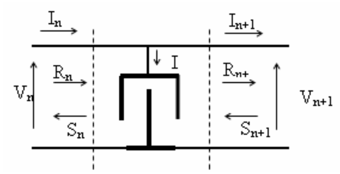


Figure 6. Elementary cell of IDT

where V_n and V_{n+1} are respectively the input and output terminal voltages and I_n and I_{n+1} the currents flowing into and out from the network, R_n and S_{n+1} the incident wave amplitudes, and R_{n+1} and S_n the scattering waves amplitudes associated with SAWs .

The transmission matrix of elements t_{ij} is:

$$\begin{bmatrix} R_{n+1} \\ S_{n+1} \\ V_{n+1} \\ I_{n+1} \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} & t_{13} & 0 \\ t_{21} & t_{22} & t_{23} & 0 \\ 0 & 0 & 1 & 0 \\ t_{31} & t_{32} & t_{33} & 1 \end{bmatrix} \cdot \begin{bmatrix} R_n \\ S_n \\ V_n \\ I_n \end{bmatrix} \qquad (9)$$

We can cascade the transmission matrices of all the N cells to obtain a transmission matrix $[Q_T]$ for the complete IDT [8],

$$[Q_T] = \begin{Bmatrix} F_{11} & F_{12} & F_{13} & 0 \\ F_{21} & F_{22} & F_{23} & 0 \\ 0 & 0 & 1 & 0 \\ -F_{31} & -F_{32} & -F_{33} & 1 \end{Bmatrix} \qquad (10)$$

with ,

$$F_{11} = \cos(\delta L) - j\,\frac{\beta}{\delta}\sin(\delta L),$$

$$F_{12} = -j\,\frac{\kappa}{\delta}\sin(\delta L),$$

$$F_{13} = \frac{\beta\,\zeta - \kappa\,\zeta^*}{\delta^2}\left[1 - \cos(\delta L)\right] + j\,\frac{\zeta}{\delta}\sin(\delta L),$$

$$F_{21} = j\,\frac{\kappa^*}{\delta}\sin(\delta L),$$

$$F_{22} = \cos(\delta L) + j\,\frac{\beta}{\delta}\sin(\delta L),$$

$$F_{23} = \frac{\beta\,\zeta^* - \kappa^*\zeta}{\delta^2}\left[1 - \cos(\delta L)\right] - j\,\frac{\zeta^*}{\delta}\sin(\delta L),$$

$$F_{31} = -4\frac{\beta\varsigma^* - \kappa^*\varsigma}{\delta^2}\left[1 - \cos(\delta L)\right] - 4j\frac{\varsigma^*}{\delta}\sin(\delta L),$$

$$F_{32} = 4\frac{\beta\varsigma - \kappa\varsigma^*}{\delta^2}\left[1 - \cos(\delta L)\right] - 4j\frac{\varsigma}{\delta}\sin(\delta L),$$

$$F_{33} = j\,\omega\,C\,L - \frac{4j}{\delta^3}\left(2\,\beta\,|\zeta|^2 - \kappa\,\zeta^{*2} - \kappa^*\zeta^2\right)\left[\delta L - \sin(\delta L)\right].$$

In these equations,

$$\delta = \sqrt{\beta^2 - |\kappa|^2} \qquad (11)$$

A similar matrix $[Q_R]$ can be obtained for the reflector and is given by [8],

$$[Q_R] = \begin{Bmatrix} H_{11} & H_{12} & 0 & 0 \\ H_{21} & H_{22} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{Bmatrix} \qquad (12)$$

with :

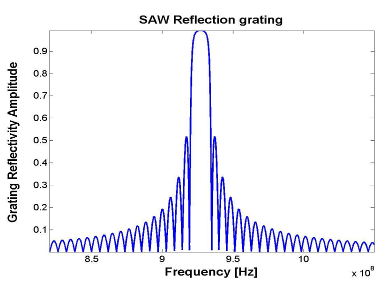
$$H_{11} = \cos(\delta_r\ L_r) - j\ \frac{\beta_r}{\delta_r}\ \sin(\delta_r\ L_r),$$

$$H_{12} = -j\ \frac{\kappa_r}{\delta_r}\ \sin(\delta_r L_r),$$

$$H_{21} = j\ \frac{\kappa_r^*}{\delta_r}\ \sin(\delta_r L_r),$$

$$H_{22} = \cos(\delta_r\ L_r) + j\ \frac{\beta_r}{\delta_r}\ \sin(\delta_r\ L_r)$$

where δ_r is the self-coupling coefficient, κ_r is the coupling complex coefficient and κ_r* its conjugate and L_r is the length of the reflector. For the following figure, we have: $\lambda = 5.48\mu m$, freq = 927 MHz, Nr = 80 fingers, k^2 = 5.8%, h = $8*10^{-8}$m



D. Transmission Matrix of Resonator

Now consider the one port SAW resonator composed of one IDT between two shorted metal strip arrays at two ends of the propagation path. By combining each equivalent circuit of the IDT, propagation paths and reflectors, the complete equivalent circuit of the SAW resonator can be obtained, as shown in Fig.7.

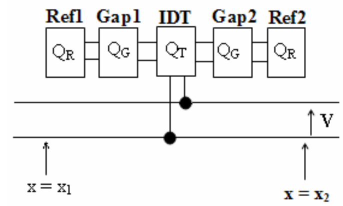


Figure 7. Cascading matrix elements.

If we put T as the entire transfer matrix of the resonator, T_{ij} can be obtained by cascading connection of the matrix for each element:

$$[T]=[Q_R][Q_G][Q_T][Q_G][Q_R] \qquad (13)$$

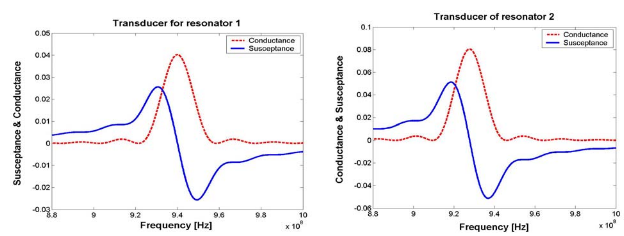
where Q_T , Q_R , Q_G are the transfer matrices for the IDT, the reflector and the free surface distance, respectively. This [T] relates the input quantities to the output quantities:

$$\begin{bmatrix} R_{N+1} \\ S_{N+1} \\ V_{N+1} \\ I_{N+1} \end{bmatrix} = [T] \cdot \begin{bmatrix} R_1 \\ S_1 \\ V_1 \\ I_1 \end{bmatrix} \qquad (14)$$

By applying the appropriate boundary conditions $R_1 = 0$ at x= x_1, and $S_{N+1} = 0$ at x=x_2, we can obtain the admittance of the one-port SAW resonator is given by,

$$Y = T(4,3) - T(4,2)\ \frac{T(2,3)}{T(2,2)} \qquad (15)$$

Using this equation giving Y, various effects of parasitic and matching elements could be taken into account in the simulation. These figures were traced by using the parameters which are in table I.



III. APPLICATION TO ZNO /SI SAW LADDER FILTER ANALYSIS

Our modelling was applied to the 3 step ladder ZnO /Si SAW filter shown in Fig. 8a. The design parameters of the series and parallel resonators are given in Table 1. The series resonators have a slightly higher resonant frequency than that of the parallel ones in order to realize a band - pass characteristics.

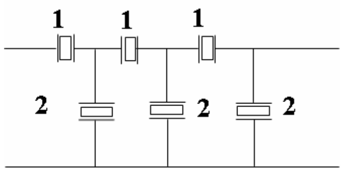


Fig.8a. Structure of the designed ladder-type filter.

TABLE 1 : DESIGN PARAMETERS OF A LADDER-TYPE FILTER.

Acoustic wavelength λ_1 , λ_2 [µm]	λ_1 = 5.32 λ_2 = 5.48
Number of fingers in each IDT(Pairs)	$Nt_{1=2}$=50.5 pairs
Number of fingers in each reflector	$Nr_{1=2}$=80 trips
aperture	W_1=80 λ_1 W_2=160 λ_2
Metal film thickness for 1 and 2	800 Å
Metallization ration	0.5
ZnO thickness (h_{ZnO}) for 1 and 2	1.1µm

Fig. 8b presents our theoretical and experimental results. We obtained the experimental frequency response without the use of external inductors or capacitors for impedance matching to 50 Ω. This filter had a center frequency of 945 MHz, a minimum insertion loss of 1.5 dB and a stop-band attenuation greater than 30 dB in the frequency range below that of the pass-band.

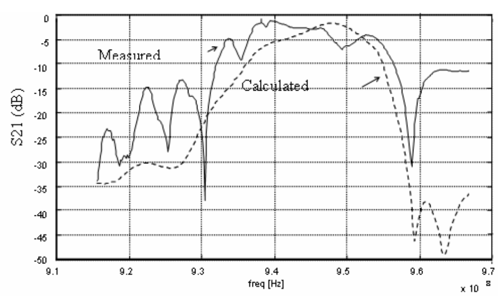


Fig.8b. Measured and calculated frequency responses of the designed ladder-type filter.

Inside the bandwidth, the experimental insertion loss of the filter exhibits two dips around 935 MHz and 950 MHz. This is probably due to the parasitic elements not introduced in the theoretical modelling (the inductance connected to the parallel and series resonators, and the capacitance to the input port, the capacitance to the output port, and the capacitance in between each resonator of the filter).All these parasitic elements may explain the discrepancy between the experimental and calculated results. A better theoretical response in the bandwidth of the filter would require optimizing the design, in particular with both non identical series resonators and non identical parallel resonators.

IV. CONCLUSION

In this paper, we proposed a COM approach that includes the SAW dispersion effects to calculate the frequency response of a layered ZnO/Si SAW filter. The effective permittivity approach was used to calculate the frequency dependencies of the electromechanical coupling coefficient, displacements and electrical potential of surface waves in the layered system.The frequency dependencies of the COM parameters have been calculated and the theoretical and experimental results for a 3 –step ladder type ZnO/Si SAW filter have been given. They clearly show that the dispersive effect has to be taken into account in the design. A further improvement of the modelling would be to introduce all the parasitic elements.

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