AlN-on-Si SAW filters: influence of film thickness, IDT geometry and substrate conductivity

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***Abstract*— In this paper we analyze the frequency response of surface acoustic wave (SAW) filters built on (00·2)-oriented AlN films deposited on silicon substrates. The experimental scattering parameters (S_{ij}) of the filters were fitted using our own circuital model that takes into account the theoretical response of the ideal SAW along with all the external and internal parasitic effects. We discuss the relation between the different circuital elements and the physical properties of the SAW device (geometry, substrate resistivity, thickness of the piezoelectric layer, etc.) and the parasitic effects due to the packaging and the wire bonding. On the basis of this analysis, some guidelines for the design of SAW structures with an optimum frequency response are given.**

Keywords- SAW filters; AlN; electrical model; stray elements.

I. INTRODUCTION

Surface acoustic wave (SAW) filters are currently used for many industrial applications. Compared to conventional piezoelectric materials (quartz, lithium niobate, lithium tantalite), aluminum nitride (AlN) films offer the possibility of being integrated in monolithic silicon technologies, as they can be deposited at low temperature on silicon substrates, providing devices with high SAW propagation velocities. Moreover, the opposite values of the temperature coefficient of delay for silicon and AlN make this pair of materials particularly suitable for implementing thermally stable SAW devices.

The frequency response of AlN-based SAW filters is mainly determined by the piezoelectric properties of the AlN layer, which determine the value of the electromechanical coupling factor (k^2) [1]. However, other parasitic effects may affect seriously the performance of the filters. Some of them, such as the packaging and the wire bonding [2], are external to the SAW device, whereas others may arise from the device itself, as in SAW filters built on non-piezoelectric substrates. For AlN films deposited on conductive silicon, the interaction between the interdigital transducers (IDTs) and the substrate produces electromagnetic feedthrough (EMF) and capacitive couplings [3], which modify significantly the performance of the device diverting it from the ideal behavior.

In this paper, we analyze the influence of external and internal parameters on the frequency response of SAW filters built with AlN layers of a given piezoelectric response deposited on silicon substrates. The parameters examined are the AlN film thickness, the geometry and nature of the IDTs, and the resistivity of the substrates. The scattering parameters (S_{ij}) of the devices were fitted using a specific circuital model that we developed previously to obtain the accurate value of k^2 for AlN films [4]. The different components of this circuital model are associated with the physical characteristics of the SAW device and with the parasitic effects related to the packaging and the wire bonding.

II. EXPERIMENTAL

AlN films with thickness between 0.15 µm and 3 µm were deposited by r.f. reactive sputtering in a mixture of Ar and N_2. As substrates we used Si (100) wafers with resistivities of 10 Ω·cm and 8000 Ω·cm. Before the deposition of AlN, some wafers were covered with a 300 nm-thick molybdenum layer. This provided us with substrates of different conductivities. The deposition conditions were set to obtain pure (00·2)-oriented films, a condition that is essential to achieve a significant piezoelectric response [5, 6].

SAW filters of different geometries (shown in table I) were built on top of the AlN layer by patterning two pairs of IDTs in 100 nm-thick chromium or molybdenum films. The SAW devices were mounted into a test fixture specifically designed for this purpose [7] and bonded with Al wires with a diameter of 25 µm. The length of the wires varied between 3 mm and 10 mm. The RF response of the SAW devices was obtained by measuring their two port scattering parameters (S_{ij}) with an Agilent 8753ES network analyzer.

TABLE I. GEOMETRIES OF THE IDTS.

Geometry	***N***	**λ (µm)**	***M* (λ)**	***W* (µm)**	***A* (cm²)**
	no. of fingers	***wavelength***	***distance between IDTs***	***finger overlap***	***IDTs area***
M2-40	50	40	50	1000	$1.45 \cdot 10^{-2}$
M2-20	100	20	100 - 250	300	$7.58 \cdot 10^{-3}$
M2-12	100	12	200	200	$4.06 \cdot 10^{-3}$
M1-40	41	40	50	1880	$1.67 \cdot 10^{-2}$

III. RESULTS AND DISCUSSION

Fig. 1 shows the S_{ij} parameters measured in several SAW devices made with AlN films of similar piezoelectric characteristics deposited on different substrates. In all cases the frequency response of S_{11}, S_{21} (= S_{12}) and S_{22} is far from ideal, revealing the existence of parasitic elements that affect the functionality of the device.

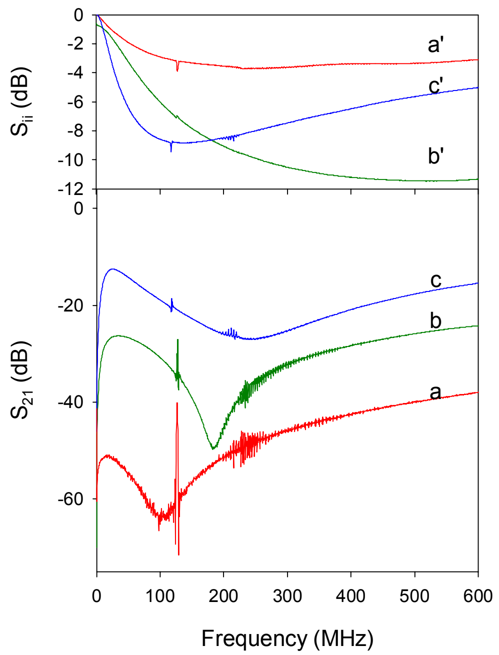

Figure 1. Set of S parameters measured in a typical device fabricated on a) 8000 Ω·cm Si substrate b) 10 Ω·cm Si substrate, and c) Mo-covered Si substrate.

The main deviation from the ideal filter response consists in a significant reduction in the out-of-band rejection observed in devices built on low-resistivity substrates. In these cases, a drop of the in-band response is also observed.

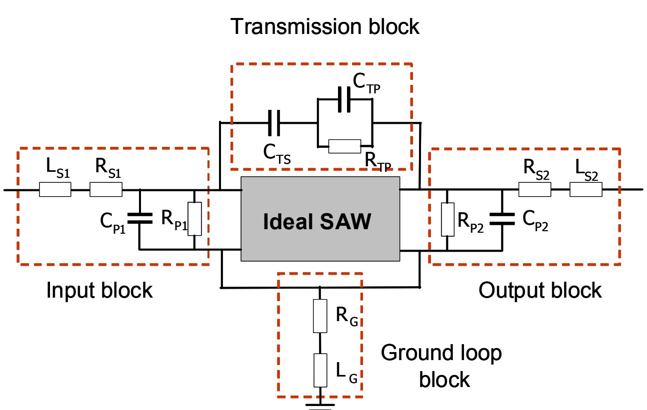

Figure 2. Circuital model

To investigate the origin of these deviations, the experimental scattering parameters (S_{ij}) were fitted using computations based on the circuital model of Fig. 2. This model includes the two-port circuit of an ideal SAW filter [1] and a series of components grouped in four blocks, which take into account the parasitic elements. The *Input* and *Output* blocks contain components that model the impedances at the input and output ports respectively, which are responsible for the reflection of the input and output signals. The *Transmission* and *Ground-loop* blocks simulate the parasitic transmission of the signal through the substrate and the air (electromagnetic feedthrough).

It is very difficult to separate the effect of each individual component on the response of the SAW filter. As a rule, the components of the *Input* and *Output* blocks tend to impede the inflow of signal to the input IDT and the outflow of signal from the output IDT, respectively. This results in a decrease of the effective transmission parameter (S_{21}) over all the frequencies, independently of the parasitic transmission. The reduction of S_{21} in the transmission band is equivalent to a reduction in the effective electromechanical coupling factor, as was discussed in [4]. On the other hand, the parasitic transmission through the *Transmission* and *Ground-loop* blocks tends to increase the S_{21} parameter over the whole frequency range, reducing the rejection of the filter. The effect of each component of the different blocks depends on the frequency: capacitive components act preferentially at low frequencies, whereas inductive components take effect at high frequencies.

The components of the different blocks, related either to parasitic reflections or to transmissions, depend on different technological issues. We have analyzed the dependence of each of these elements on the technological parameters (substrate conductivity, AlN film thickness, IDT geometry, packaging) in order to study the impact of the strays on the filter response and get some clues to design well-performing filters on silicon substrates.

A. *Input and Output blocks*

In the *Input* and *Output* blocks, the series resistances R_{S1} and R_{S2} are related to the resistance of the metallic electrodes and vary between 10 Ω and 25 Ω in the devices analyzed, without following any clear trend. The effect of increasing R_S is a uniform shift of S_{21} upwards. The series inductances L_{S1} and L_{S2} depend clearly on the length of the wire loops used to connect the device to the test fixture. Thus, the longer the wire, the higher the value of L_S. However, this parameter has a small effect on S_{21} over the frequency range of interest. The parallel resistances R_{P1} and R_{P2} are related to the AlN resistance between the two electrodes of each IDT. In accord with the insulating character of the AlN film, their values are usually very high (more than 20 MΩ), although they can get as low as 10 Ω when there are conduction paths between the IDTs (either between the electrodes, resulting from a defective photolithographic process, or through the substrate, due to pinholes in the AlN film). The components mentioned so far are not related to the design of the device, but are due to the packaging and to technological failures, and their effect can be reduced through a careful packaging process. As for the parallel input and output capacitances C_{P1} and C_{P2}, it is important to note first that their values are not related to the IDT capacitance, which has been previously calculated according to [8] and incorporated into the ideal SAW block. The experimental data reveal that C_{P1} and C_{P2} increase linearly with the area of the electrodes and the inverse of the AlN thickness, as expected. Additionally, they decrease as the resistivity of the substrate becomes higher (see Fig. 3), so that these components would disappear if insulating substrates, such as lithium niobate, sapphire or quartz, were used. Their values are consistent with the capacitance of the metal-insulator-semiconductor (MIS) capacitor formed by the electrode, the AlN layer and the Si substrate in the inversion region.

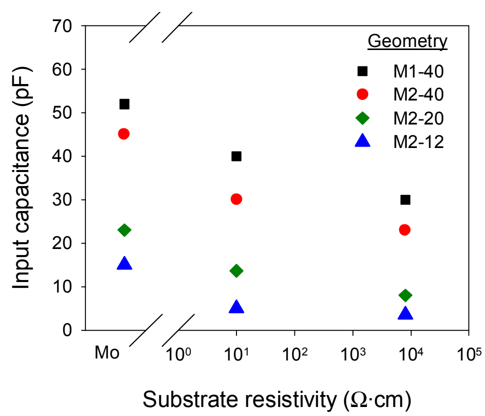

Figure 3. Input capacitance (C_{Pi}) as a function of the substrate resistivity for devices with different geometries.

We have also studied the influence of the separation between the IDTs (M) by making devices with a geometry of the type M2-20 and different values of *M* on 10 Ω·cm silicon substrates. We have observed that this geometrical parameter does not affect the components of the *Input* and *Output* blocks.

B. *Transmission block*

Most of the components of the *Input* and *Output* blocks are predominantly affected by effects extrinsic to the device, such as the bonding wires or technological issues. The components of the *Transmission* block (C_{TS}, C_{TP} and R_{TP}) are affected mostly by intrinsic properties of the device, such as the substrate resistivity, the AlN thickness and the IDTs geometry (see Fig. 4). The values of C_{TS} are related to the coupling of the electrical signal to the substrate, which is more intense for lower substrate resistivities and AlN thicknesses and for larger IDT areas.

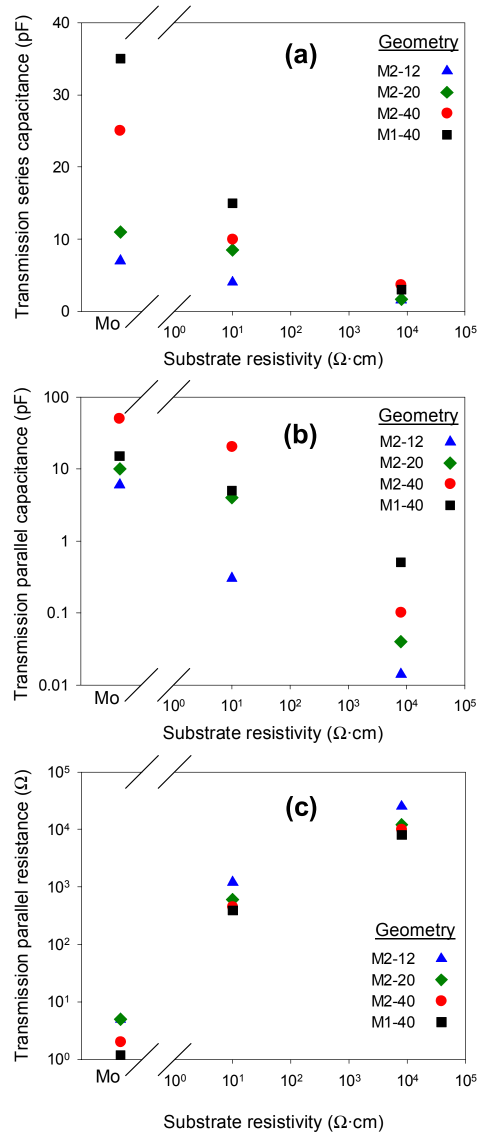

Figure 4. Transmission block components a) C_{TS}, b) C_{TP}, and c) R_{TP} as a function of the substrate resistivity for various IDTs geometries.

The separation *M* between the electrodes does not affect the value of C_{TS}, which confirms that this element models the coupling of the signal to the substrate. Its values are nearly half those of C_{P1} and C_{P2}.

C_{TP} and R_{TP} model the signal path through the substrate. C_{TP} decreases rapidly as the resistivity of the substrate increases, whereas R_{TP} behaves in the opposite manner. Both parameters depend significantly on the geometry (overlap *W* and separation *M*) of the IDTs (see Fig. 5) but not on the thickness of the AlN layer. Therefore, they are related to the geometry and resistance of the conductive substrate between the input and output ports (transmission path).

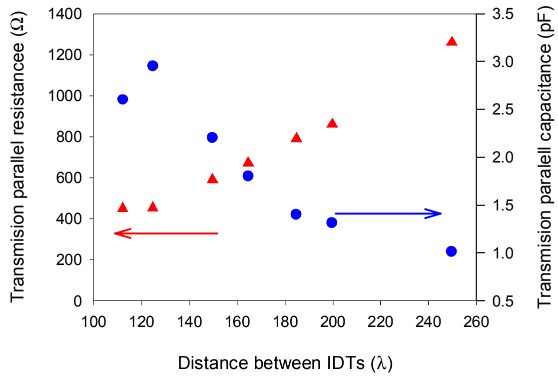

Figure 5. R_{TP} and C_{TP} as a function of the distance *M* between the IDTs.

C. *Ground-loop block*

Like the *Transmission* components (C_{TP} and R_{TP}), the *Ground-loop* components L_G and R_G are also related to parameters intrinsic to the device, particularly to the substrate resistivity and the IDT geometry (see Figs. 6 and 7). This means that the *Ground-loop* constitutes, with the *Transmission* block, the set of components that model the transmission of the electromagnetic signal between the two ports. However, the experimental results demonstrate that L_G is also affected by the inductive effect of the bonding to ground, whose effect is similar to that of L_{S1}. This inductance is in parallel with that due to the substrate, which is much lower and, thus, dominates the overall effect. L_G and R_G do not depend substantially on the AlN thickness, but depend on the distance between the electrodes (see Fig. 8). This shows that, besides accounting for the bond wire effects, these components depend on the transmission of the signal from one electrode to the other. Thus, we can conclude that both the components of the *Transmission* block and those of the *Ground-loop* block model the transmission of the electrical signal through the substrate and depend on the substrate resistivity and the geometry of the device, which settles the travel path of the signal between the two IDTs.

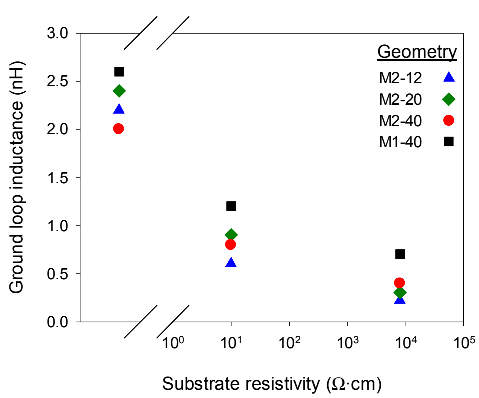

Figure 6. *Ground-loop* inductance L_G as a function of the substrate resistivity for various IDTs geometries.

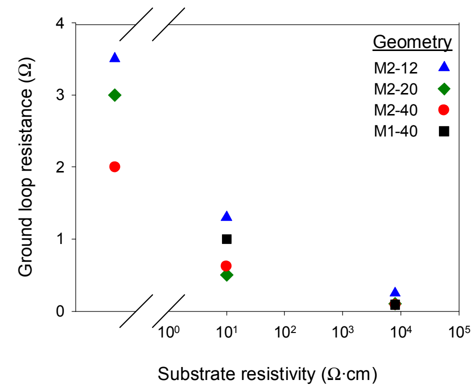

Figure 7. *Ground-loop* resistance R_G as a function of the substrate resistivity for various IDTs geometries.

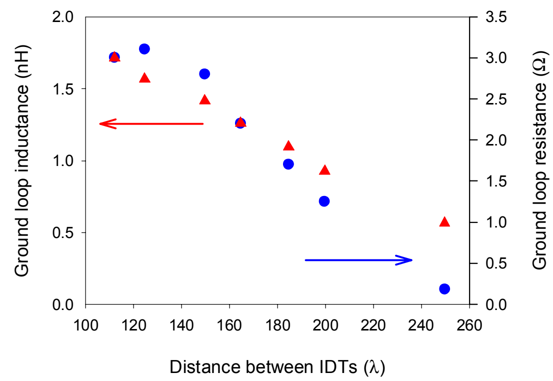

Figure 8. Components of the *Ground-loop* L_G and R_G as a function of the distance *M* between IDTs.

We have shown that some of the stray elements are related to the fabrication and packaging of the device (wire bonds, electrode resistances, resistance between the electrodes). Some other elements depend on the conductive nature of the substrate, while others depend on the geometry of the IDTs (as it defines to what extent the signal will interact with the substrate). All these results, summarized in table II, allow us to suggest some guidelines to optimize the frequency response of SAW filters based on AlN films deposited on silicon substrates.

TABLE II. DEPENDENCE OF THE COMPONENTS OF THE CIRCUITAL MODEL ON THE PHYSICAL PROPERTIES OF THE DEVICE.

Component	Major dependence	Typical values
L_{Si}	Test fixture	6 – 10 nH
R_{Si}	Metallization	10 – 25 Ω
R_{Pi}	Technology	$10 - 20 \cdot 10^6$ Ω
C_{Pi}	Electrode area / Substrate / Thickness	5 – 60 pF
C_{TS}	Electrode area / Substrate / Thickness	2 – 35 pF
C_{TP}	IDT separation / Substrate	0.2 – 50 pF
R_{TP}	IDT separation / Substrate	10 – 25 k Ω
R_G	Test fixture / IDT separation / Substrate	0 – 4 Ω
L_G	IDT separation / Substrate	0 – 2.5 nH

The most detrimental effects of the stray elements are those due to the conductive character of the substrate, as they produce a significant drop of the out-of-band rejection by reducing the out-of-band loss over the whole frequency range. We can minimize these effects by using highly-resistive silicon substrates, which reduces the values of the transmission and *Ground-loop* impedances. Substrate resistivities of a few thousands Ω·cm are required to achieve an out-of-band rejection similar to that of an ideal SAW filter (26 dB). Fig. 9 shows the effects of using substrates of different resistivities in the frequency response of the SAW device. This behavior has been simulated with our model by including only the components of the *Transmission* and *Ground-loop* blocks.

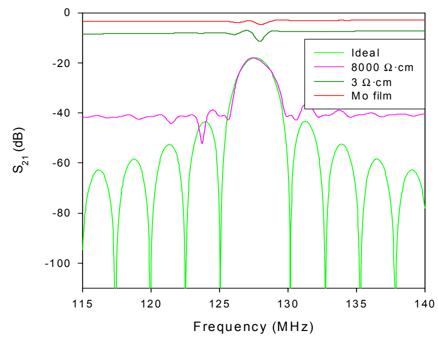

Figure 9. Effect of the *Transmission* block parameters on the response of a SAW filter (no input elements considered).

To improve further the frequency response of a filter, the in-band loss must be as low as possible. The in-band loss of a SAW filter is mainly determined by the piezoelectric quality of the AlN layer. However, it is also affected by the input and output impedances that attenuate the signal supplied to the piezoelectric material. We have found that this can reduce the effective electromechanical coupling factor (k_{eff}^2) by a factor of up to 20 times. To decrease the in-band loss, C_{P1} and C_{P2} must be as low as possible. The use of high-resistivity substrates contributes to reduce C_{P1} and C_{P2} and thus to improve the SAW response.

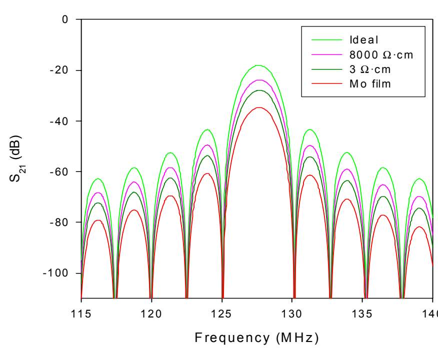

Figure 10. Effects of the *Input* block parameters on the response of a SAW filter (no transmission elements considered).

Additionally, C_{P1} and C_{P2} are the only components of the *Input* and *Output* ports that depend on the design of the filter. They can be minimized by reducing the electrode area (including the collector bars and bonding pads) and by increasing the thickness of the AlN film. Other technological parameters, such as the distance between the IDTs or the resistance of the electrodes, are of secondary importance. Fig. 10 shows the effects of the input parameters, related to the different substrate resistivities, on the response of SAW devices. The frequency responses were simulated with our model after removing the *Transmission* and the *Ground-loop* blocks.

IV. CONCLUSIONS

We have built SAW devices based on piezoelectric AlN films on silicon substrates in order to analyze how the frequency response of SAW filters on conductive substrates is distorted by the existence of stray elements. The effects of the stray elements include the electromagnetic feedthrough between both IDTs through the substrate and the reflections of the signal at the input and output ports due to the mismatch between the impedances of the device, the source and the load. The stray elements can cause an unacceptable reduction of the out-of-band rejection and an effective increase of the in-band loss. These effects must be taken into account in order to analyze the frequency response. One can minimize all these effects and obtain well-performing AlN-on-silicon SAW filters by using highly resistive substrates, by carefully designing the IDTs geometry and by using adequate packaging methods.

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REFERENCES

[1] C. K. Campbell, “Surface Acoustic Wave Devices for Mobile and Wireless Communications”, Academic Press, San Diego, 1998.

[2] D. Jatkar and B. Beker, “Effects of package parasitics on the performance of SAW filters”, IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, Vol. 43 (6), pp. 1187–1194, 1996.

[3] M. Clement, L. Vergara, J. Sangrador, E. Iborra, and A. Sanz-Hervás, “SAW characteristics of AlN films sputtered on silicon substrates”, Ultrasonics, vol. 42, pp. 403-409, 2004.

[4] E. Iborra, L. Vergara, J. Sangrador, M. Clement, A. Sanz-Hervás, and J. Olivares, “A model for the accurate determination of the electromechanical coupling factor of thin film SAW devices on non-insulating substrates”, Proceedings of IEEE International Ultrasonics Symposium 2004, vol. 3, pp. 1880-1883, 2004.

[5] M. Clement *et al.*, “Influence of sputtering mechanisms on the preferred orientation of aluminum nitride thin films”, J. Appl. Phys., vol. 94, pp. 1495-1500, 2003.

[6] E. Iborra *et al.*, “Effect of particle bombardment on the orientation and the residual stress of sputtered AlN films for SAW devices”, IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control, vol. 51, pp. 352-358, 2004.

[7] Agilent, “In-fixture measurements using vector network analyzers” Application note AN 1287-9.

[8] M. W. den Otter, “Approximate expressions for the capacitance and electrostatic potential of interdigitated electrodes”, Sensors and Actuators A, vol. 96, pp. 140-144, 2002.