AlScN-Based SAW Resonator with Improved RF Performance Using High-Resistivity Silicon Substrate

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***Abstract*—Surface acoustic wave (SAW) resonators have been the core RF filtering technology for mobile communication due to their inherent high quality-factor (Q) and small physical size. This paper investigates the effect of the substrate resistivity on the performance of the SAW resonators. For this study, the RF performance of SAW resonators, fabricated on 1 μm thick C-axis Scandium (Sc)-doped AlN (AlScN) thin-film with 6% Sc on alternative wafer stack-ups with Low Resistivity (LR) and High Resistivity (HR) Silicon (Si) substrates are analyzed. To capture the effect of the substrates on the AlScN-based SAW resonator performances, the Figure of Merit (FoM) per unit of Sc percentage (i.e., $\frac{FoM}{Sc\%}$ or FoM / Sc%) is introduced in this work. The FoM / Sc% of the SAW resonators with 400 nm and 450 nm IDT width on LR Si substrate with 1 μm Tox are found to be 68 and 55 respectively . The same are 100 and 128 for the SAW devices with similar design built on HR Si without oxide and 102 and 120 for the SAW devices on HR Si with 2 μm oxide. The observed enhanced performance using HR Silicon substrates is attributed to the reduction of substrate RF losses.**

***Index Terms*—AlScN, RF Resonator, SAW resonator, Q factor, FoM, $k_t^2 \times Q$**

I. Introduction

A plethora of SAW-based RF filtering architectures have been demonstrated to date, however, the majority of them is limited by ultra-narrow fractional bandwidth (FBW) due to being directly proportional to the effective electromechanical coupling coefficient (k_t^2) of their piezoelectric substrate. Sc-doped Aluminium Nitride ($Al_{1-x}Sc_xN$ where, x = atomic percentage of Sc) is being increasingly explored with the purpose of increasing k_t^2 of the resonators, however at the expense of their quality factor (Q). Different groups have reported work on AlScN-based SAW resonators, listing the performance of the resonators in terms of their k_t^2, Q and the Figure of Merit (FoM) which is defined as the product of k_t^2 and Q, i.e., FoM = $k_t^2 \times Q$ [1], [2]. It is also well established that the k_t^2, and, thereby, the FoM of AlScN-based SAW resonators, can be improved significantly with increasing the Sc-doping concentration [1]. Furthermore, it has been observed that the RF losses are dependent on the substrate type onto which the AlN or doped AlN thin films are deposited [1], [3], [4].

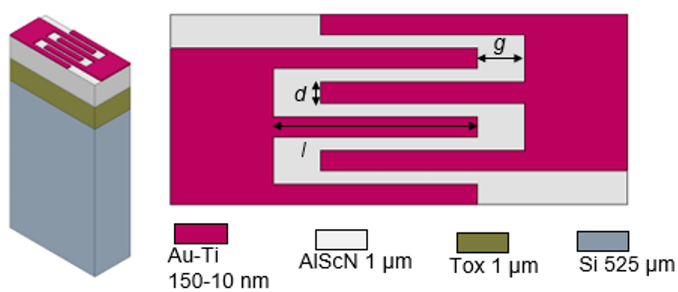


Fig. 1. 3D geometry and the conceptual illustration of three pairs of the interdigitated transducers (IDTs) of a SAW resonator. The SAW resonator is designed with 50 IDT pairs and 100 reflectors (omitted in the figure) that are placed at a distance 450 nm from the IDT edge. The indicated geometrical dimensions are as follows: g = 2 μm, d = 450 nm and l = 110 μm.

But, it becomes challenging to differentiate the effect of the substrates and Sc-concentration for improving the performance of the AlScN-based SAW resonators. Therefore, to capture the effect of substrate type on SAW device performance, the normalized Figure of Merit (FoM) with respect to Sc percentage (i.e. FoM / Sc%) is introduced in this work. This paper carries out a detailed study on the SAW resonator performance as a function of alternative material parameters. Specifically, this paper studies the effect of the Si substrate resistivity in the presence or absence of thermal oxide (Tox) and compares the performance with the AlScN-based SAW resonators from the literature.

II. Design and Simulation

To evaluate the SAW resonator performance dependence on alternative material parameters, SAW resonators were designed and fabricated with three different Si substrate configurations: (i) LR Si with 1 μm thick Tox, (ii) HR Si with 2 μm thick Tox, and, (iii) HR Si without oxide. The study was carried out with two designs, design-A with 400 nm IDT width / inter-IDT spacing (acoustic wavelength (λ) = 1.6 μm) and design-B with 450 nm IDT width and gap (λ = 1.8 μm). Fig. 1 shows the device stack that consists of a 1 μm thin-film of AlScN on Tox coated substrate. Both, LR and HR Si substrates are 525 μm thick. The electrode material used for IDTs is Au-Ti with 150 nm – 10 nm thickness.

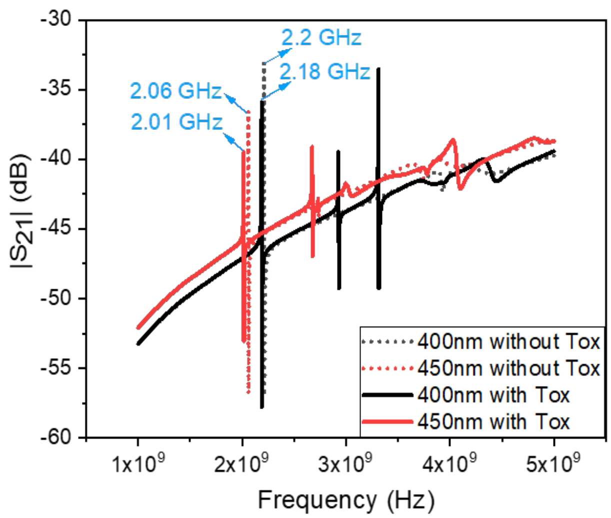


Fig. 2. Consolidated simulation results for the designed SAW resonators

The COMSOL Multiphysics-simulated series resonance frequencies for the design-A device for the stack up without and with Tox were found to be 2.2 GHz and 2.18 GHz respectively. The simulated frequencies for the design-B device were found around 2.01 GHz and 2.06 GHz for the stack up without and with oxide layer. This small increase in frequency (of the order of a few 10s of MHz) for resonators on the AlScN stack without Tox is attributed to higher effective acoustic velocity. Fig. 2 depicts the consolidated simulation results of all the resonators for two different stack configurations. The modal analysis plot for design-A and design-B are shown in Fig. 3(a) and Fig. 3(b) respectively. The simulated Rayleigh mode for design-A device was found to be around 2.1 GHz, whereas, the same for the design-B device was around 2.0 GHz.

Results and Discussion

To experimentally validate the effect of the material parameters, SAW resonators were fabricated on AlScN deposited silicon substrates. The AlScN (with 6% Sc) thin-films were deposited using an in-house magnetron sputtering PVD tool. The SAW resonators were patterned using electron-beam lithography tool followed by lift-off of Au-Ti thin-film of 150 nm – 10 nm thickness. Fig. 4(a) shows the SEM images of a fabricated SAW resonator. The IDT details are provided in Fig. 4(b). The measurement results of the design-A and design-B resonators on LR Si with 1 μm thick Tox, on HR Si with 2

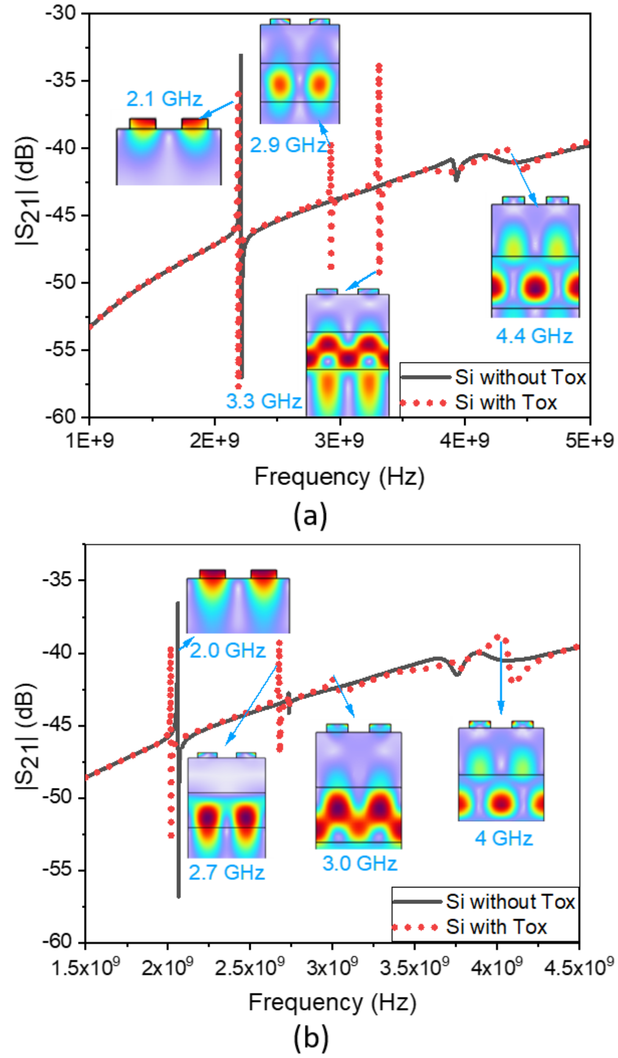
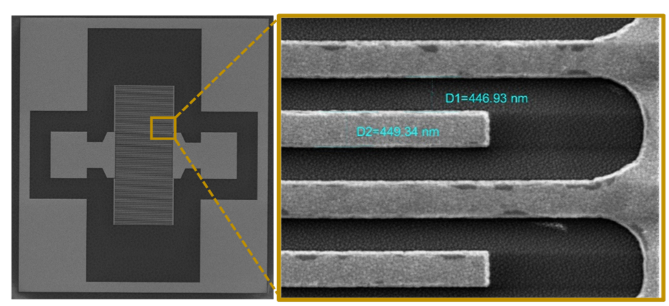


Fig. 3. Simulated modal analysis of (a) design-A resonator with 400 nm IDT width, (b) design-B resonator with 450 nm IDT width



(a) (b)

Fig. 4. SEM image of an example case of a fabricated SAW resonator that comprises of 50 IDTs and two pairs of 100 reflectors. (a) Full geometry, (b) A close-up view of the IDTs patterned using e-beam lithography.

μm thick Tox and on HR Si without Tox are shown in Fig. 5(a) and Fig. 5(b) respectively.

The performance of the resonators were evaluated via 2-port s-parameter measurement. The device without oxide showed higher series resonance frequency compared to the device with oxide. Similar phenomena was observed in the COMSOL

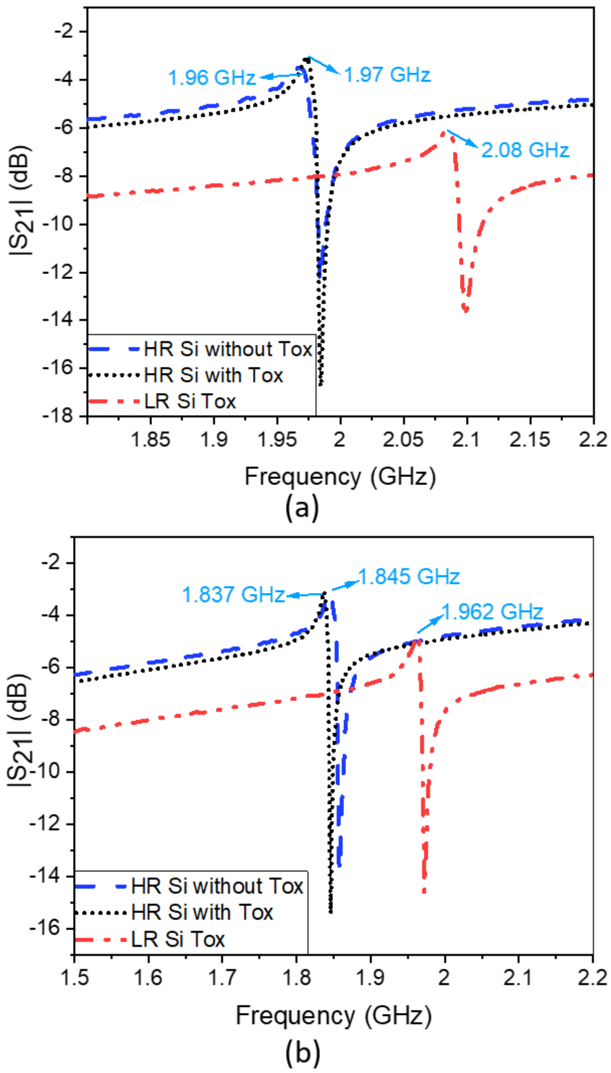


Fig. 5. Measurement results of (a) design-A resonator with 400 nm IDT width, (b) design-B resonator with 450 nm IDT width.

simulation. From the measured results shown in Fig. 5 it can be observed that the design-A SAW device on LR Si with oxide has a frequency of 2.08 GHz and the design-B device resonates at 1.962 GHz which finds a good match with the simulated results. Furthermore, for the design-A resonators on HR Si substrates, with and without oxide, exhibit resonant frequencies of 1.97 GHz and 1.96 GHz respectively, whereas, for design-B resonators the frequencies are 1.837 GHz and 1.845 GHz, respectively. Similar trend of frequency difference for HR Si substrates, with and without oxide, is also observed in the simulation results as shown in Fig. 3.

The equivalent lumped circuit parameters of the SAW resonators were extracted from the s-parameter measurement results via the mBVD model (refer Fig. 6). The extracted lumped parameters of design-A resonators with and without the presence of Tox on HR Si substrate are shown in Table I. The performance metrics of all the fabricated resonators are tabulated in Table II. The FoM / Sc% of the fabricated SAW resonators are calculated and compared with the same from

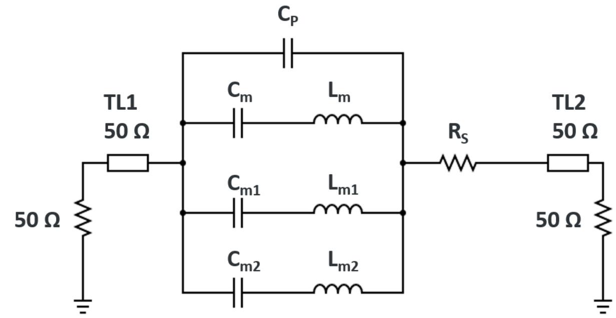


Fig. 6. mBDV model of a SAW resonators

state-of-the art AlScN-based SAW resonators.

It is observed that the extracted value of FoM / Sc% for the design-A resonator on LR Si with Tox stack is 68 whereas for the design-B device on the same stack is 55 . Similarly, the FoM / Sc% on HR Si with Tox for the design-A device is 102 and for the design-B resonator, it is 120. Furthermore, for the HR Si without Tox stack up, the FoM / Sc% for the design-A device is 100 and for the design-B device it is 128.67.

Analysing the overall outcome of the measurement results from resonators with different design and substrate, it can be determined that performance of the resonators can be improved using HR substrates. This improvement in performance is because of the reduction in RF losses in HR Si substrates compared to the devices on LR Si substrates. It can also be noted that the difference between FoM / Sc% for SAW devices on HR Si with and without oxide is insignificant. This indicates that the Tox layer on HR Si does not provide any additional benefit towards reduction of RF losses.

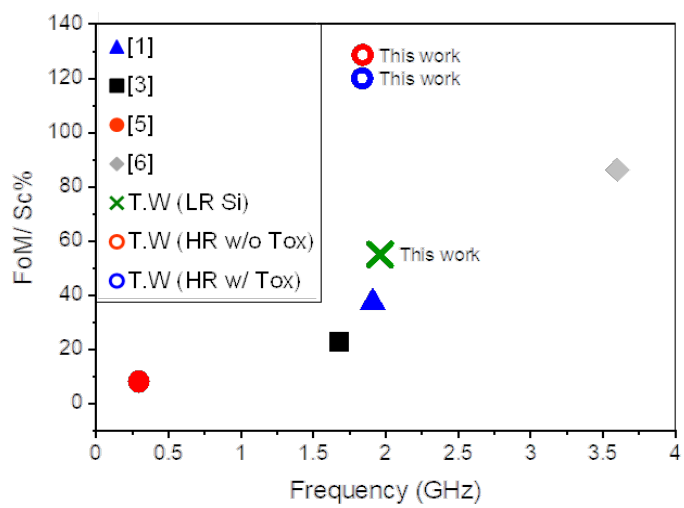


Fig. 7. Performance comparison in terms of FoM per unit Sc% for the SAW resonators developed in this work with similar SAW resonators from literature.

Fig. 7 presents a comparison between FoM / Sc% of the resonators developed in this work with similar Sc-based SAW resonators from recently reported literature. Anli Ding et al. in [1] have reported work on 1 μm thick AlScN thin-film with 32% and 23% Sc. Zhijian Hao et al. [3] have reported performance of SAW devices on AlScN with 11.8%, 43% and

TABLE I
EXTRACTED EQUIVALENT LUMPED PARAMETERS FROM MBVD MODEL

Design-A 400 nm IDT SAW resonators	$\mathbf{C_m}$ **(fF)**	$\mathbf{C_{m1}}$ **(fF)**	$\mathbf{C_{m2}}$ **(fF)**	$\mathbf{L_m}$ **(μH)**	$\mathbf{L_{m1}}$ **(μH)**	$\mathbf{L_{m2}}$ **(μH)**	$\mathbf{R_S}$ **(Ω)**	$\mathbf{C_P}$ **(pF)**
Substrate: HR Si with 2 μm Tox	1.094	0.978	0.288	6.817	7.639	26.04	5.1	0.572
Substrate: HR Si without Tox	1.274	1.095	1.034	5.785	6.741	7.162	3.6	0.588

TABLE II
SUMMARY TABLE

Material stack	**Performance parameters**	**400 nm IDT SAW resonators (λ = 1.6 μm)**	**450 nm IDT SAW resonators (λ = 1.8 μm)**
LR Si with 1 μm TOX	Q	436	474
	k_t^2%	0.94	0.7
	FOM	4.1	3.3
	FoM / Sc%	68	55
HR Si without TOX	Q	259	600
	k_t^2%	2.3	1.28
	FOM	6	7.7
	FoM / Sc%	100	128
HR Si with 2 μm TOX	Q	552	746
	k_t^2%	1.1	0.97
	FOM	6.1	7.2
	FoM / Sc%	102	120

46%, and, Wenbo Wang et al. in [5] have also worked on AlScN-based SAW resonators with 27% Sc [6]. From Fig. 7, it can be seen that the current work has better FoM / Sc% with the high resistivity silicon. This improvement is attributed to the use of superior quality of AlScN thin-film developed in-house supplemented by optimal design incorporation for this material.

CONCLUSION

In this work, the effect of resistivity of Si substrate on the performance metrics of the SAW resonators has been studied. It is found that the FoM / Sc% of SAW resonators on HR Si substrate shows remarkable improvement over its LR counterpart. It is also observed that the oxide layer on HR Si does not provide any further improvement. This work will be continued in future towards further improvement of the performance of the SAW resonators for filter applications by improving the design and increasing Sc% in AlScN thin-film.

ACKNOWLEDGMENTS

This work has been supported in part by Science Foundation Ireland (SFI) project No. 20/RP/8334 and by Tyndall's internal award "Catalyst 2021". The authors would like to acknowledge the support provided by Tyndall SP&S team, especially, Daniel O'Connell and Graeme Maxwell. The authors are also thankful to the Prof. Cian O'Mathuna, the center Head of Micro & Nano Systems, Tyndall, for his continuous support and encouragement.

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