Investigation of 20% Scandium-doped Aluminum Nitride Films for MEMS Laterally Vibrating Resonators

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***Abstract* — This paper reports on the investigation of 1 µm thick films of 20% Scandium-doped Aluminum Nitride (ScAlN) for the making of piezoelectric MEMS laterally vibrating resonators (LVRs). The ScAlN films, which can be sputter-deposited such as undoped Aluminum Nitride (AlN) films, were used to demonstrate high performance resonators. These devices showed quality factor (Q_s) in excess of 1000 in air centered around 250 and 500 MHz and enhanced electromechanical coupling (k_t^2) in the range of 3.2-4.5%. This k_t^2 is double the value of what has been achieved on similar resonators made out of AlN films. A 3-dB Q_s of 1300 has been recorded both for 1-port and 2-port resonators at 250 and 500 MHz, while a maximum Q_s of 1500 has been recorded for a 1-port resonator at 500 MHz. Along with experimental results from actual devices, this work also reports the etching characteristics of the piezoelectric material under Cl_2/BCl_3 chemistry to attain high selectivity and straight sidewall with a SiO_2 hard mask. More broadly, enhancement of resonators design and fabrication process, suppression of spurious modes and increase in the concentration of Sc (theoretically up to 40%) will lead to significant performance improvements for many classes of piezoelectric MEMS, especially tunable filters.**

***Index Terms* — MEMS, AlN, ScAlN, Resonators, LVR, fabrication, Scandium-doped**

I. INTRODUCTION

RF filtering technologies based on piezoelectric MEMS resonators have been widely investigated and successfully deployed over the past decade due to their size and outstanding performance. Especially for mobile phone filtering applications, systems based on thin film bulk acoustic wave resonators (FBARs) and surface acoustic wave (SAW) devices have been proposed and commercialized on a large scale, setting the threshold for any future improvement of this technology. The challenge to enhance filter's performance in terms of lower insertion losses and wider bandwidth is still an active research topic, especially spurring the interest for new classes of materials such as doped-AlN [1] and thin films of Lithium Niobate (LN) [2]. Research is currently focused in overcoming fabrication constraints and device performance for both materials, which are still far from the theoretical maximum.

Different solutions based on lateral vibrating resonators (LVRs) or contour mode resonators (CMR) have been previously proposed to allow multi-frequency fabrication on a single die and achieving a good Figure of Merit (FOM=$k_t^{2\cdot}Q_s$) at the same time, which respectively limits FBARs and SAW devices. Despite encouraging Q_s achieved with AlN-based systems, the electromechanical coupling (k_t^2) of these devices remains very limited (1-2%), preventing the construction of wideband filters. Furthermore, the low dielectric constant (ε_r=9) of AlN needs arraying for application requiring high static capacitances (nominally C_0 of a resonator). X-cut [3] and Y-cut LN [4] alternatives have also been proposed, due to high ε_r (43) and k_t^2 (10-30%). Although results indicates good performance, the increased fabrication complexity and cost of thin film transfer still limits LN resonators large-scale implementation.

A possible solution for both performance enhancement and fabrication complexity is the use of sputtered Scandium-doped films of AlN. The most promising study reports values of k_t^2 up to 8% for 40% Sc-doped AlN [1][5], roughly 4 times higher than non-doped AlN [6]. Despite lower k_t^2 and ε_r compared to LN resonators, ScAlN devices may show higher quality factor, Q_s, leading to higher overall FOM. Finally, ScAlN devices allow better system integration compatibility with CMOS and easier fabrication due to thin film sputtering.

This paper describes the design and fabrication of 20% Sc-doped MEMS LVRs resonators by building off the knowledge developed through the design and fabrication of similar AlN devices. The main goals of this work are to demonstrate: 1) higher k_t^2 (~2x) compared to non-doped AlN, 2) ease of fabrication process compared to lithium niobate thin films, 3) fabrication of multi-frequency devices (250 MHz – 500 MHz) on the same substrate.

II. RESONATOR DESIGN AND FABRICATION

A. General layout and geometries

The resonators described in this work are made of interdigital electrodes (IDT) on top of a suspended plate of ScAlN thin film (1 µm). A patterned Pt bottom electrode of 100 nm deposited on 10 nm of Cr adhesion layer is present and grounded through laterally etched vias connected to ground pads. The presence of this bottom electrode increases the resonator static capacitances, C_0, and allows the fabrication of two-port networks. Different finger pitches, plate sizes and number of Al top electrodes have been selected for the test based on the previously developed AlN resonators designs. Device center frequencies were designed to range from 200 MHz to 500 MHz based on the density and Young’s modulus reported in literature for 20% Sc-doped AlN films [7]. Since the characteristics of the films were not known at the time of the tape-out, the overall design is not fully optimized for ScAlN. The plate’s length was varied between 130 µm and 200 µm, the width between 50 µm and 100 µm with a number of electrodes equal to 6. IDT coverage was kept constant at 50%. Starting from this configuration, some 1-port devices have been included in the layout. For this particular class of devices the bottom electrode is floating and vias are not present. Contact pads with 150 µm pitch in a ground-signal-ground (GSG) configuration are used for measurements.

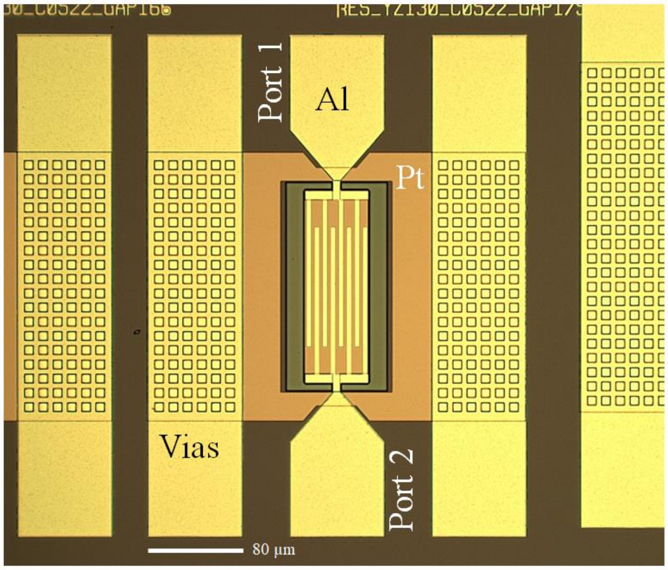

Fig. 1. General layout for a ScAlN resonator.

B. Process flow

The main fabrication steps for ScAlN resonators are shown in Fig. 2. The process flow is based on the same sequence previously developed for AlN resonators. Due to the different behavior of the materials during etching, recipes have been properly modified and adjusted through direct experimentation with samples of ScAlN films.

As first step (step 1 in Fig.2), the Pt bottom electrode was patterned on top of a HR silicon wafer (ρ=15000 Ω·cm) using DC sputtering (Perkin Elmer 6J) and lift-off (AZ 4110). The thickness of the metal was set to 100 nm. To ensure adhesion between the metallic layer and the Si surface, 10 nm of Cr was pre-sputtered with the same tool. Cr is required to make the process compatible with hydrofluoric acid (HF) wet etch used to strip the oxide mask in subsequent steps. Successively, ScAlN was deposited on top of the wafer through sputter deposition (step 2 in Fig. 2) by AMS Inc. Then, a SiO_2 hard mask was patterned for the release pit etching (step 3 in Fig. 2). SiO_2 was deposited on the ScAlN surfaces with a Trion PECVD tool. The overall thickness was set at 2.5 µm according to the etch rate selectivity between SiO_2 and ScAlN in chlorine-based RIE for the selected recipe (1:2). In order to pattern the SiO_2, 50 nm of Cr were sputtered with the Perkin Elmer 6J and patterned using chlorine-based RIE (Versaline). AZ 4110 photoresist was used to define the pattern to be transferred in the thin Cr layer. Later, oxide was etched using fluorine-based RIE (Plasmatherm 790). ScAlN layer was etched using chlorine-based RIE (Versaline). Compared to AlN, for the same recipe parameters (Pressure: 5 mTorr, ICP power: 400 W, RF power: 125 W, Cl_2 flow: 25 sccm, BCl_3 flow: 5 sccm, Ar flow: 70 sccm), the measured etch rate of ScAlN was 4 times lower (50 nm/min vs 200 nm/min). For this reason the ICP power was increased to 600 W, the RF power to 350 W and the BCl_3 flow to 15 sccm to ensure an etch rate of 150 nm/min.

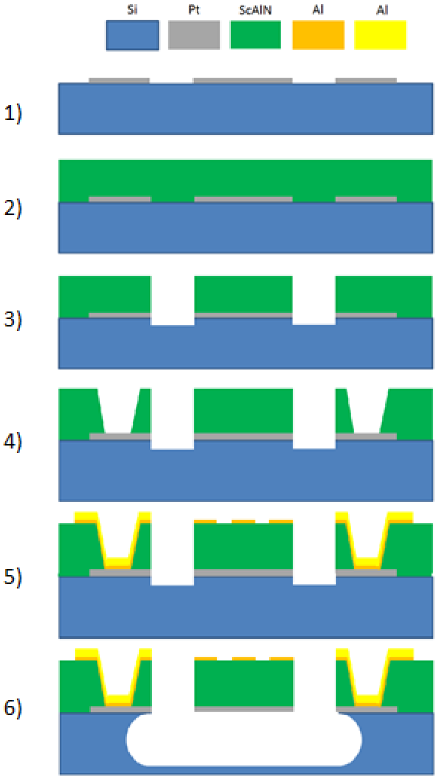

Fig. 2. Fabrication flow for ScAlN devices.

The same step used to define the device structure was also used to pattern the via (Step 4 in Fig. 2). Another oxide layer was deposited. The etch step was subdivided into several sub-steps of 10 second each in order to properly stop the etch on the Pt layer. Step (5) involved a double sputtering deposition and lift-off (AZ 4110) of AlSiCu. 100 nm thick of AlSiCu was deposited on the ScAlN substrate for the fingers and the base of the pad, while another 200 nm were sputtered for the pads to ensure good adhesion for wire bonding. As last step (6), the devices were released using XeF_2.

III. RESULTS

A. SEM pictures and fabrication issues

After fabrication and release, the devices were visually inspected with an SEM. As shown in Fig. 3, redeposition effects are present on the resonator surface and on the outer frame in the form of thin flakes. Furthermore, some out-of-plane bending of the resonator can be noticed. Even if the average stress measured in the Sc-doped film was lower than 100 MPa, the stress gradient is sufficient to deform the plates once released. The sidewalls of the resonator appear smooth and range between 70 and 75 degrees, as shown in Fig. 4.

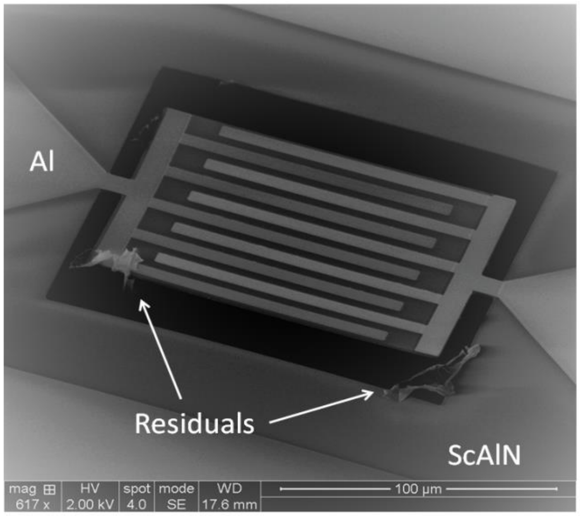

Fig. 3. SEM picture of 250 MHz 2-port ScAlN resonators. Flakes due to redeposition are visible on the edge of the resonator and on the outer frame.

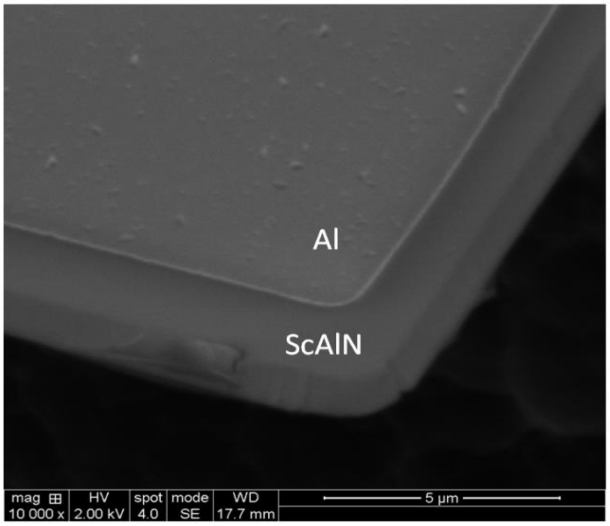

Fig. 4. Sidewall detail of a ScAlN resonator.

B. Admittance response of resonators

In order to extract the admittance response of the fabricated resonators, their S-parameters were measured using a vector network analyzer (VNA). These set of parameters were then converted to Y-parameters. Starting from the Y-parameters data, the resonator equivalent electrical parameters were extracted by fitting the responses to a Butterworth-Van Dyke (BVD) model [8], both for 1 and 2-port devices (Fig. 5).

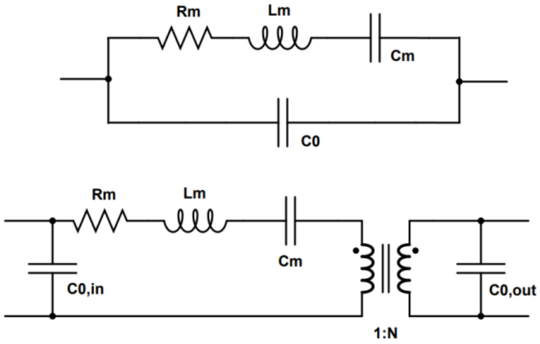

Fig. 5. BVD models for 1 and 2-port resonators.

Measured responses and fitted results, with equivalent electrical parameters, are shown in Fig. 6-8 for different resonators and frequencies (both 1 and 2-port devices).

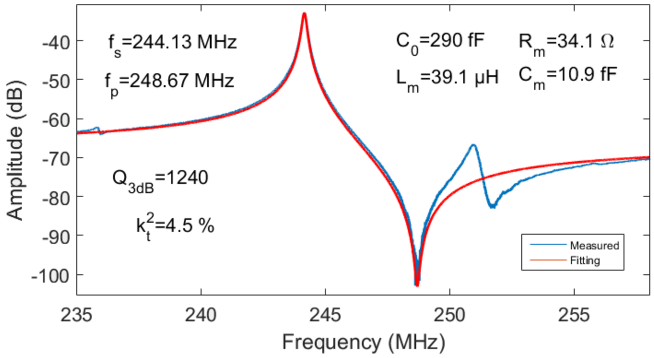

Fig. 6. Y11 admittance response for 1-port resonator (250 MHz) without de-embedding.

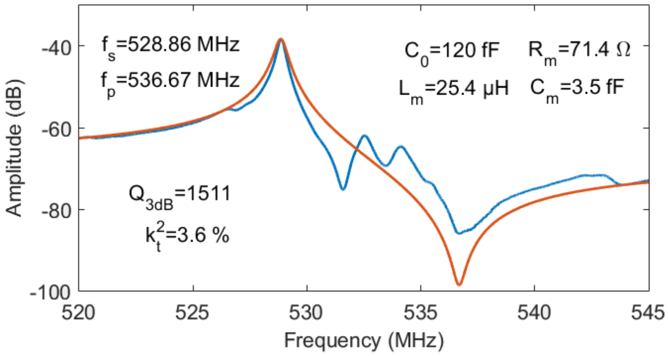

Fig. 7. Y11 admittance response for 1-port resonator (500 MHz) without de-embedding. This resonator shows the highest Qs recorded for this type of device.

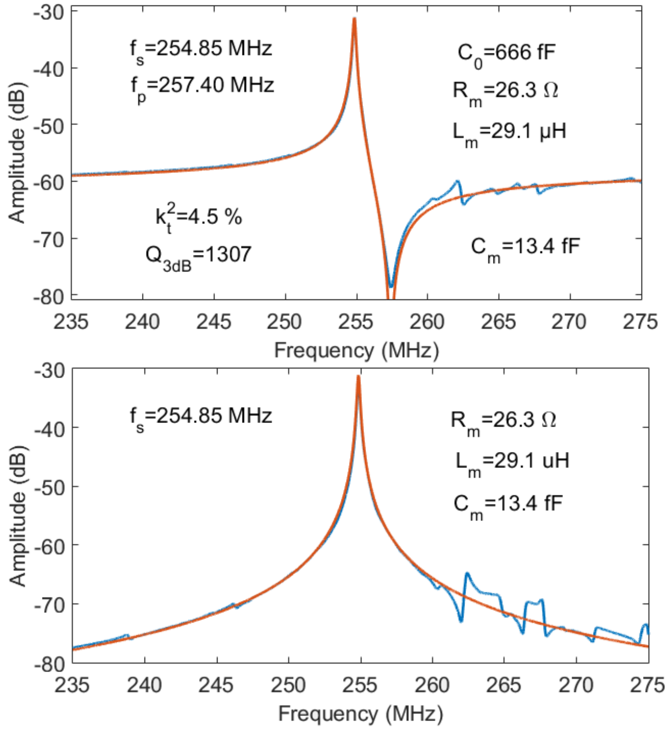

Fig. 8. Y11 and Y12 admittance responses for 2-port resonator (250 MHz) without de-embedding.

IV. CONCLUSIONS

In this paper 20%-doped Sc AlN films were investigated for the making of piezoelectric MEMS LVRs. The combination of high k_t^2 (4.5%) and Q_s (1300 for 1 and 2-port resonators) achieved with ScAlN devices yielded an overall FoM (k_t^2 Q_s) of about 60. Considering the early stage of this investigation of Sc-doped AlN films, two different approaches can be adopted to improve the quality of these resonators. The first is to improve the fabrication process, eliminating redeposition, improving the sidewall quality and better controlling the stresses of the thin film. We believe that these improvements would enhance the Q_s of the resonators. The second is to increase the doping concentration of Scandium up to the maximum theoretical optimal value of 40%. A limiting factor that emerged during the fabrication of ScAlN LVRs is the presence of spurious modes, which would need to be controlled for filtering applications.

Further experiments and tests are required to better investigate the material behavior and mechanical properties, such as density (ρ), dielectric constant (ε_r) and stiffness matrix coefficients.

The results presented herein are very encouraging and we believe that, through additional work, we will be able to devise the next generation of sensors and filters for a broad class of commercial applications.

V. ACKNOWLEDGMENTS

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