A 5.3 GHz $\text{Al}_{0.76}\text{Sc}_{0.24}\text{N}$ Two-Dimensional Resonant Rods Resonator with a Record $k_t^2$ of 23.9%

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Abstract—This work reports on the measured performance of an Aluminum Scandium Nitride (AlScN) Two-Dimensional Resonant Rods resonator (2DRR), fabricated by using a Sc-doping concentration of 24%, characterized by an ultra-low impedance (~25 $\Omega$) and exhibiting an all-time world record electromechanical coupling coefficient ($k_t^2$) of 23.9% for AlScN resonators. In order to achieve such unprecedented performance, we identified and relied on optimized deposition and etching processes for highly-doped AlScN films, aiming at achieving high crystalline quality, low density of abnormal grains in the 2DRR’s active region and sharp lateral sidewalls. Also, the 2DRR’s unit-cell has been acoustically engineered to maximize the piezo-generated mechanical energy within each rod and to ensure a low transduction of spurious modes around resonance. Due to its unprecedented $k_t^2$, the reported 2DRR opens exciting scenarios towards the development of next generation monolithic integrated radio-frequency (RF) filtering components. In fact, we show that 5th-order 2DRR-based ladder filters with fractional bandwidths (BW) of ~11%, insertion-loss (IL) values of ~2.5 dB and with >30 dB out-of-band rejections can now be envisioned, paving an unprecedented path towards the development of ultra-wide band (UWB) filters for next-generation Super-High-Frequency (SHF) radio front-ends.

Keywords— Aluminum Scandium Nitride, Two-Dimensional-Resonant-Rods, $k_t^2$, Acoustic Filters, Acoustic Metamaterials

I. INTRODUCTION

In the last two decades, microacoustic resonators (µARs) have played a key role in integrated 1G-to-4G radios, providing the technological means to achieve compact radio-frequency (RF) filters with low loss and moderate fractional bandwidths (BW<4%). More specifically, Aluminum Nitride (AlN) based filters have populated the front-end of most commercial mobile transceivers due to the good dielectric, piezoelectric and thermal properties exhibited by AlN thin-films and because their fabrication process is compatible with the one used for any Complementary Metal Oxide Semiconductor (CMOS) integrated circuits (ICs) [1][2]. Nevertheless, the rapid growth of 5G and the abrupt technological leap expected with the development of sixth-generation (6G) communication systems are expected to severely complicate the design of future radio front-ends by demanding Super-High-Frequency (SHF) filtering components with much larger fractional bandwidths than achievable today. As the bandwidth of any acoustic filter is directly proportional to the electromechanical coupling coefficient ($k_t^2$) exhibited by its forming resonators, a large effort has been recently made to identify new µAR-designs or alternative piezoelectric materials granting larger $k_t^2$ than what attained by the existing counterparts, all relying on the transduction of Lamb modes [3] in piezoelectric plates. Even more, since the acoustic filter topologies granting the highest BW leverage a set of electrically coupled µARs with different resonance frequencies, a large attention has also been paid to identify new acoustic technologies allowing to monolithically integrate µARs with different lithographically defined resonance frequencies ($f_{res}$), without increasing fabrication complexity and costs. In this regard, new AlN µARs have been recently reported, still relying on the transduction of acoustic waves in plates but achieving boosted $k^2$ values by leveraging: i) a segmented electrode excitation [4], ii) the excitation of dispersive $S_i$ modes [5][6], iii) the transduction of two-dimensional modes [7] around the dilatation frequency or iv) the spatial sampling of piston-like displacement modal distributions through an engineered dispersion of simultaneously transduced Lamb modes [8]. Nevertheless, while these new µARs enable a lithographic frequency tunability and a boosted electromechanical coupling
spectral purity of the 2DRR’s frequency response. It is spurious modes affecting the transduction efficiency and the acoustic energy within each rod, and to suppress any undesired the 2DRR’s unit-cell to 2DRR’s active region and a low residual stress, along with the lowest density of AlScN abnormally oriented grains in the aiming at achieving the best possible film crystallinity, the deposition and etching recipes for highly doped AlScN films, performance in the reported 2DRR, we developed optimized [27]. In order to achieve such unprecedented electromechanical attainment by AlScN FBARs (SoA) AlN devices, such as Film-Bulk-Acoustic-Resonators (FBARs [10]). Differently, a larger \(k^2\) than what attained by AlN FBARs has been enabled through the recent invention of Two-Dimensional-Resonant-Rods resonators (2DRRs [12]). 2DRRs leverage the exotic dispersive features of acoustic metamaterials, built out of thin-film corrugated piezoelectric layers, to simultaneously achieve a significant lithographic frequency tunability (>10%) and a \(k^2\) exceeding what possible when relying on un-corrugated piezoelectric plates, like the ones used to build FBARs. Nevertheless, the maximum theoretical \(k^2\) value of AlN 2DRRs (~9%) remains severely limited by the AlN piezoelectric coefficients, making AlN 2DRRs not usable to make ultra-wideband (UWB) filters for next-generation SHF front-ends. For this reason, in this work we designed, fabricated and tested a 2DRR relying on Aluminum Scandium Nitride (AlScN [13]), a piezoelectric material attained by doping AlN with scandium dopants and characterized by piezoelectric coefficients growing proportionally to the scandium-doping concentration (Sc\(_{\text{v}}\)). More specifically, the 2DRR reported in this work relies on a 24% Sc\(_{\text{v}}\) value, it has a resonance frequency (\(f_{\text{res}}\)) of \(~5.3\) GHz and it shows the highest \(k^2\) (23.9%) ever demonstrated in AlN or AlScN µARs [5-28]. A comparison of the \(k^2\) achieved by the 2DRR reported in this work with what attained by the previously reported highest-\(k^2\) AlN and AlScN counterparts is provided in Figure 1. It is worth emphasizing that the 2DRR reported here achieves a \(k^2\) value that is even higher than what attained by AlScN FBARs (21%) exploiting higher Sc\(_{\text{v}}\) values [27]. In order to achieve such unprecedented electromechanical performance in the reported 2DRR, we developed optimized deposition and etching recipes for highly doped AlScN films, aiming at achieving the best possible film crystallinity, the lowest density of AlScN abnormally oriented grains in the 2DRR’s active region and a low residual stress, along with sharp sidewalls after the AlScN etch. Even more, we engineered the 2DRR’s unit-cell to trap the piezoelectrically generated acoustic energy within each rod, and to suppress any undesired spurious modes affecting the transduction efficiency and the spectral purity of the 2DRR’s frequency response. It is important to point out that the \(k^2\) exhibited by the 2DRR reported in this work is also one of the highest ones ever reported for any SHF µARs, including the ones leveraging piezoelectric materials, like LiNbO\(_3\), that are not manufacturable through CMOS-compatible fabrication processes (Table I).

In the following, we will first present the design and main operational features of the reported 2DRR by means of Finite Element Methods (FEM). We will numerically show how the proper engineering of the 2DRR’s unit-cell permits to generate stop-bands, inhibiting the acoustic propagation out of each piezo-active rod. This provides key means to really leverage the high electromechanical performance of 2DRRs, as well as to improve the spectral purity of their frequency response by suppressing the propagation of Lamb waves moving across the 2DRR’s corrugated film. Then, we will describe the complete fabrication process we followed to build the reported 2DRR. More specifically, we will discuss the processing conditions we identified and relied on to deposit and etch the Al\(_{0.76}\)Sc\(_{0.24}\)N film used by the reported 2DRR. Also, we will show the results of a complete set of material characterization experiments, demonstrating the high-quality of the sputtered and etched AlScN film used to build the 2DRR presented here. Later, we will showcase the 2DRR’s electrical performance, extracted by a direct measurement through conventional RF characterization tools. Finally, given the 2DRR’s exceptional electromechanical performance demonstrated in this work, we will discuss the new unveiled potential for building future SHF acoustic filters, with unprecedented ultra-wide BWs and low insertion-loss values.

### II. 2DRRs - Principle of Operation

A 2DRR consists of a group of identical unit-cells, each one formed by one rod symmetrically placed between two identical trenches (see Figure 2). Each trench relies on a thin piezoelectric layer (with thickness \(T_t\)), deposited onto a full grounded metal plate. The rods, instead, use a thicker piezoelectric layer with thickness \(T_s\). Also, the portion of the piezoelectric layer used for the rods is fully covered by a set of metallic strips responsible for the 2DRR’s electrical transduction, together with the grounded bottom metal plate. As we analytically demonstrated in [12], the corrugated 2DRR’s structure enables unique acoustic dispersion features that do not exist in un-corrugated plates. For instance, it permits to generate stop-bands, inhibiting the acoustic propagation of real energy out of each 2DRR’s unit-cell. This makes each unit-cell able to efficiently transduce its

| Ref. | Material | CMOS Compatible | \(f_{\text{res}}\) [GHz] | \(k^2\) |
|------|----------|-----------------|----------------|---------|
| [29] | LiNbO\(_3\) | No | 5 | 26% |
| [30] | LiNbO\(_3\) | No | 9.5 | 11% |
| [31] | LiNbO\(_3\) | No | 5 | 9% |
| [32] | LiNbO\(_3\) | No | 5 | 28% |
| [33] | AlN | Yes | 24 | 6% |
| [34] | AlN | Yes | 8.8 | 0.3% |
| [35] | AlN | Yes | 11 | 1.3% |
| [36] | AlScN | Yes | 9 | 5.3% |
| [37] | AlScN | Yes | 11.1 | 1.8% |
| [38] | AlScN | Yes | 19 | 3.5% |
| [39] | AlScN | Yes | 8.5 | 0.3% |

This work | AlScN | Yes | 5.3 | 23.9% |

Figure 2: Schematic view of the reported 2DRR, including 5 unit-cells. For the reported 2DRR, each unit-cell uses a rod width (\(W_r\)) of 9 \(\mu\)m, a unit-cell width (\(W_o\)) of 24 \(\mu\)m, a \(T_t\) of 350 nm and a \(T_s\) of 150 nm. Thicknesses for the (Ti/Pt) bottom metal layer and for the top (Al) metal strips are 26/50 nm and 110 nm, respectively. With regard to the reported 2DRR’s excitation strategy, the top metal strips are all connected to the same voltage polarity, whereas the bottom plate is grounded.
own rod-mode, with almost the same transduction efficiency as if it was not connected to any other unit-cells. More specifically, the corrugation in the piezoelectric film generates a reactive coupling between adjacent unit-cells that is strong enough to ensure a single frequency operation, but weak enough not to affect significantly the modal transduction within each unit-cell. Even more, the corrugated 2DRR’s structure produces artificial and lithographically defined boundary conditions, allowing to squeeze the piezo generated displacement in the rods and near the interfaces between the piezo layer and the top metallic strips. Such a unique modal characteristic, together with the fact that most of the transduced acoustic energy can then be stored in resonator volumes bounded by lateral stress-free surfaces, makes the rods more compliant to both vertical and horizontal deformations. This provides the means to achieve a higher motional capacitance ($C_m$) than attained by conventional µARs relying on one or two-dimensional modes of vibration in uncorrugated plates. Regarding the 2DRR’s excitation strategy, each rod-mode is transduced by generating a vertical electric field between the top and bottom metallic layers sandwiching each rod, and by leveraging both the $d_{31}$ and $d_{15}$ piezoelectric coefficients of the adopted piezoelectric layer. It is also worth emphasizing that the use of a corrugated piezoelectric layer permits to conveniently reshape the electric field distribution within the entire 2DRR’s volume so that just a negligible electric field exists within the trenches. This permits to avoid the undesired excitation of shear-modes from in-plane electric field components, even preventing any $k_i^2$ reductions due to electrical energy being stored out of the rods (i.e. out of the 2DRR’s active region).

### A. 2DRR –Design Flow

The 2DRR reported in this work was designed by relying on a purely acoustic finite-element simulation, aiming at identifying the optimal cross-sectional dimensions leading to the generation of a stop-band around the desired operational frequency ($f_{tar} \approx 5.3 \text{ GHz}$). In order to do so and in line with what previously found [12][14], we assumed any rod-modes to have a resonance frequency matching closely the $f_{res}$ value of the thickness-extensional (TE) mode relative to the rods’ material stack. By doing so and after selecting a specific material composition for the active region of the targeted 2DRR prototype, we were able to analytically find the $T_i$ value and the thicknesses of the two 2DRR’s metal layers ($T_{bot}=20/50 \text{ nm}$ and $T_{top}=110 \text{ nm}$) resulting into an $f_{res}$ value equal to $f_{tar}$. Later, we identified an optimal combination of rod-width ($W_i$), unit-cell width ($W_o$) and $T_i$ values, allowing to generate a stop-band around $f_{tar}$. In order to do so, we built a 2D simulation framework in COMSOL to investigate the acoustic transmission properties of the 2DRR’s corrugated structure. This relied on an input pressure source (with frequency $f_{in}$), generating an acoustic power ($P_{in}$) longitudinally flowing through the left side of a 2DRR structure formed by 5 unit-cells (the same number used for the 2DRR built in this work). A power probe was used to quantify the acoustic power level ($P_{out}$) reaching the right side of the 2DRR structure, allowing to compute a transmission coefficient ($T$, equal to $|P_{out}/P_{in}|$) capturing the ability to transmit real power across the 2DRR’s corrugated structure. Perfectly-Matched-Layers (PMLs) were also employed in our simulations to prevent undesired reflections due to acoustic scattering occurring at the outer edges of a bounded simulated geometry, which would otherwise degrade the accuracy and reliability of our results. The FEM simulated trend of $T$ vs. $f_{in}$ is reported in Figure 3, together with a schematic view summarizing the main features of our simulation framework. As evident, the designed 2DRR structure exhibits a series of nearly contiguous stop-bands for $f_{in}$ values close to $f_{tar}$, demonstrating that the interaction of the local rod resonances with the acoustic propagation characteristics of the trenches can indeed inhibit the propagation of real energy across the 2DRR structure. In other words, within the stop-bands, all the wave-vectors relative to the acoustic propagation through the trenches are imaginary. As a result, for $f_{in}$ values included in any stop-bands, there is no real power internally produced within each rod flowing out of the corresponding unit-cell, ensuring that just a weak and reactive coupling exists between adjacent unit-cells. In order to provide a visual representation of the acoustic behavior of the 2DRR structure operating within any one of its stop-bands, we report in Figure 3 the simulated modeshape of...
AlScN frequency tunability and permitting to just partially leverage the lithographic resolution, yet limiting the maximum lithographic rods (differently from our recent AlN prototype [10] using a reported here relies on a electrical response. It is also worth emphasizing that the 2DRR achieve a high model [38]. As evident, the results of our FEM simulations trend through a Modified-Butterworth-Van Dyke (MBVD) extracted the 2DRR’s expected the 2DRR’s simulated admittance ($Y_m$) between the 2DRR’s top and the bottom metal layers, with do so, we applied a continuous-wave (CW) input voltage the corrugated structure, we also simulated through FEM the to an almost nulled $|p|$ generated across the 2DRR structure by the employed pressure source for a $f_{0a}$ (5.31 GHz) coinciding with the measured $f_{res}$ value of the reported 2DRR device. Evidently and as expected, $|p|$ decays exponentially with the distance from the pressure source, leading to an almost nulled $T$ value.

After relying on purely acoustic FEM simulations to design the corrugated structure, we also simulated through FEM the electromechanical response of the resulting 2DRR. In order to so we applied a continuous-wave (CW) input voltage between the 2DRR’s top and the bottom metal layers, with frequency ranging between 3 GHz and 7 GHz. Then, arbitrarily assuming a mechanical quality factor ($Q_m$) of 200, we extracted the 2DRR’s simulated admittance ($Y$, see Figure 4), Next, we extracted the 2DRR’s expected $k^2$ by fitting the simulated $Y$ trend through a Modified-Butterworth-Van Dyke (MBVD) model [38]. As evident, the results of our FEM simulations clearly show that the designed 2DSSR can simultaneously achieve a high $k^2$ (~20%), as well as an almost spurious-free electrical response. It is also worth emphasizing that the 2DSSR reported here relies on a $W_r$ value that is much larger than $T_m$, differently from our recent AlN prototype [10] using a $W_r$ value close to the total thickness of the piezoelectric layer within the rods ($T_{tot}$, equal to $T_r+T_s$). This allows to maintain a relaxed lithographic resolution, yet limiting the maximum lithographic frequency tunability and permitting to just partially leverage the AlScN $d_{31}$ piezoelectric coefficient. Nevertheless, the 2DSSR’s corrugated structure allows to focus most of the piezoelectrically generated acoustic energy under each rod and near the interfaces between the piezoelectric layer and the top metal layer (see the modeshape in Figure 4), thus in those portions of the 2DSSR’s active region laterally bounded by closely spaced stress-free surfaces. This ensures that the highest possible transduction efficiency can be achieved, given the applied purely vertical electric field distribution.

III. FABRICATION PROCESS

The AlScN 2DSSR prototype reported in this work was fabricated on a low resistivity silicon wafer by using the process flow described in Figure 5. We first deposited and patterned a 20/50 nm-thick Ti/Pt film. Then, we deposited a 500 nm-thick Al$_{0.76}$Sc$_{0.24}$N-film by using a set of optimized deposition conditions that will be discussed in details in Section IV-a. Later, we deposited and patterned a 110 nm-thick Al layer to form the metallic strips on top of each rod. Next, we deposited and patterned a 250 nm-thick Au layer over the probing and routing areas to reduce the electrical loading. This step is critical, given the 2DSSR’s low impedance ($25 \Omega$) and its expected motional resistance ($R_m$) lower than $1 \Omega$. Then, the 2DSSR’s outer boundaries were formed by simultaneously etching both AlScN and Ti/Pt through an Inductively Coupled Plasma Reactively Ion Etching (ICP-RIE). This also allowed to generate the release pits for the structural release of the 2DSSR device. Another ICP-RIE step was then run to form the trenches. Both etching steps relied on the same SiO$_2$ hard mask, patterned twice, and on an optimized recipe discussed in Section IV-b. Finally, the device was structurally released through a XeF$_2$ isotropic etch.

IV. AlScN PROCESSING AND CHARACTERIZATION

Several challenges exist to deposit and etch AlScN films for micro- and nano- electromechanical (MEM/NEM) devices. While several groups have been recently looking at ways to epitaxially grow nm-thick AlScN films [39][40], sputtering remains the most adequate deposition technique when AlScN films with thicknesses in the hundreds of nanometers or more are needed. Therefore in this work, we relied on sputtering to deposit the Al$_{0.76}$Sc$_{0.24}$N layer used by the reported 2DSSR prototype. Since the quality of sputtered and etched AlScN
films is very sensitive to the adopted deposition and etching processes, proper procedures must be identified and followed to achieve patterned c-oriented AlScN films with the best possible crystalline orientation and with sharp sidewalls. Furthermore, the same procedures must give a low residual stress as well as a low percentage of abnormally oriented grains (AOGs). AOGs are irregularities in the crystalline structure of sputtered AlScN films, whose density tends to quickly grow with the adopted Sc\% value. Attaining a low AOG-density has shown to be fundamental to really leverage the superior electromechanical performance of highly-doped AlScN resonators [41]. Even more, the selection of higher Sc\% values makes it significantly more challenging to etch AlScN rather than AlN, especially if spatially consistent and sharp enough sidewall profiles are needed to prevent acoustic performance degradations due to mode conversion.

A. AlScN Deposition

We deposited a 500 nm-thick Al_{0.76}Sc_{0.24}N film utilizing an EVATEC CLUSTERLINE® 200 MSQ multi-source system. In particular, we relied on a DC-pulsed co-sputtering process using Al and Sc 4-inch targets (see Figure 5-b). Several deposition parameters, such as chuck height, N_2 flow and chuck temperature impact the AlScN’s crystalline quality. Also, the AOG density highly depends on the material stack on which the AlScN film is grown. For instance, a Ti/Pt stack was found to lead to fewer AOGs during the growth of the AlScN films than other metals or metal-stacks. Nevertheless, we found that the AlScN AOG density attained when using Ti/Pt heavily depends on the chuck temperature during the Ti deposition. In this regard, we show (Figure 6) two Scanned-Electron-Microscope (SEM) pictures of 500 nm-thick Al_{0.76}Sc_{0.24}N layers, deposited on top of 20 nm/50 nm Ti/Pt stacks by using the same optimized deposition recipe (see Table 2) but relying on different deposition conditions for the Ti layer. In particular, Figure 6-(a) shows a top-view of one of the sputtered Al_{0.76}Sc_{0.24}N films when setting the chuck temperature during the Ti deposition at 50°C. Evidently, a large density of AOGs was found in this case. A much more favorable AOG density was instead attained for the second Al_{0.76}Sc_{0.24}N film, sputtered on top of an identical Ti/Pt stack, yet attained by setting the chuck temperature to 500°C during the Ti deposition. As shown in Figure 6-(b), the increase of the chuck temperature during the Ti deposition allowed us to largely reduce the AlScN AOG density. Such improvement is likely due to the fact that a Ti film deposited at higher temperatures can diffuse less into the Pt layer during the AlScN deposition. In any case, the minimization of the AlScN

| Parameter                  | Value       |
|----------------------------|-------------|
| Power to Al Target         | 1000 W      |
| Power to Sc Target         | 450 W       |
| N_2 Gas flow               | 20 sccm     |
| Target to Substrate Height | 33 cm       |
| Substrate Temperature      | 350 °C      |
| Base Pressure              | 9E-8 mbar   |

Table II: Optimized Al_{0.76}Sc_{0.24}N deposition recipe

AOG density attained in this work made it possible to achieve superior quality in the AlScN film, allowing to really exploit the inherent high k^2 of AlScN 2DRRs. The optimized AlScN film was characterized in terms of both its stoichiometric composition and its rocking curve. The former was assessed by relying on Energy-Dispersive Spectroscopy (EDS). As shown in Figure 7-a, EDS provided us with the elementary composition of the deposited AlScN film on top of Ti/Pt and silicon. From the detected atomic percentages of Sc and Al, we were able to confirm a Sc concentration of ~24\%, matching closely our targeted value; b) XRD result for the same Al_{0.76}Sc_{0.24}N film. Clearly, the B-20 goniometer shows a peak at 36.2°, indicating that the deposited AlScN film has a c-oriented crystalline structure. Also, as evident from the inset, the Full-Width-at-Half-Maximum (FWHM) relative to the rocking curve of the same AlScN film is 1.9°, which proves that an AlScN film with an excellent crystalline structure has been grown. It is worth mentioning that the two remaining XRD peaks, at 28.5° and 40.1°, are associated to the Si substrate and to the bottom Pt, respectively.

B. AlScN Etching

As we mentioned in Section III, there are two AlScN
etching steps involved in the fabrication of the reported 2DRR. One step permits to create the release pits and to define the outer edges of the suspended piezoelectric membrane after its structural release. The other step consists, instead, in a partial etching of the AlScN film, aiming at generating the 2DRR’s corrugated structure. For both steps, the most important goal is the generation of sharp etching sidewalls, preventing any performance degradations due to acoustic mode conversion. As discussed in Section III, both etching steps were run by using ICP-RIE, a technique offering a combination of both physical and chemical etching that is particularly effective whenever thin-films with well-aligned crystalline structures need to be etched. Therefore, we benefitted from the good crystalline orientation attained by our deposited AlScN film (see Figure 7) even during the characterization of the AlScN etching recipe. We started by setting the Cl₂/BCl₃/Ar gas flow composition to 10/6/28 sccm, as well as the ICP/RF-Bias to 600/300 W. This set-up has recently showed to be effective in etching highly doped AlScN films. Soon, we realized that the chamber pressure (P) during the etching process was a critical parameter to control the AlScN sidewall angle (θ). In particular, we verified that the lateral etching responsible for the AlScN sidewall profile can be largely reduced by lowering P during the etch, even allowing to exploit higher etching rates. In Figure 8, we report three Scanned Electron Microscope (SEM) pictures showing the sidewall profile of three pieces of the Al₀.₇Sc₀.₃N film discussed in Figure 7 when using the etching parameters reported in Table III, as well as three different P values (30 mT, 20 mT and 10 mT). Evidently, relying on the lowest P value permits to achieve the best θ (72°), as well as the highest etching rate (110 nm/min, thus 2.5 times faster than the one attained when relying on a P value of 30 mT). Even more, the amount of physical etching ensured by the adoption of such a low P value suffices to etch even the Ti/Pt layer under the AlScN film. The optimized parameters of the etching recipe we developed in this work are summarized in Table III.

V. EXPERIMENTAL RESULTS

After building the reported 2DRR through the fabrication process discussed in Section III, we characterized its electromechanical performance by means of a conventional RF characterization. Such characterization targeted the extraction of the measured 2DRR’s admittance vs. frequency (Figure 9) through a Vector Network Analyzer (VNA). The measured 2DRR’s response was then fitted by using an MBVD model to extract its electromechanical parameters, including: the statistic capacitance (C₀), the kᵣ value, Qₘ, Rₘ, the series resistance due to electrical routing (Rₛ), the parallel resistance (R₀) due to dielectric losses in the substrate, the mechanical figure of merit (FoM⁽℠⁾ = kᵣ²Qₘ) and the unloaded figure-of-merit (FoM). FoM was calculated as FoM = (2πf₀C₀)|Y(f₀)|, where f₀ is the anti-resonance frequency and |Y(f₀)| is the admittance magnitude at f₀.

Table IV: MBVD-Fitted electromechanical parameters for the 2DRR reported in this work (see Figure 9)

| Parameter | C₀ [fF] | Rₛ [Ω] | Rₘ [Ω] | R₀ [Ω] |
|-----------|---------|--------|--------|--------|
| Value     | 1250    | 0.7    | 7.7    | 1.5    |
| Parameter | kᵣ²    | Qₘ     | FoM⁽℠⁾ | FoM*   |
| Value     | 23.9    | 101    | 12     | 24     |

*Calculated as FoM = (2πf₀C₀)|Y(f₀)|, where f₀ is the anti-resonance frequency and |Y(f₀)| is the admittance magnitude at f₀.
was extracted from the measured admittance at the 2DRR’s parallel resonance frequency in favor of a more general performance evaluation, independent of the $C_0$ value selected for the reported 2DRR prototype. All the fitted parameters are listed in Table IV. As evident, the built 2DRR operates at 5.31 GHz and shows a record-high $k^2$ of 23.9%, while being characterized by a capacitive impedance with magnitude approximately equal to $24 \Omega$. It is worth emphasizing that such a high $k^2$ value exceeds what expected from our FEM simulation (~19%). Thanks to its superior $k^2$ and despite its relatively low $Q_m$ (101), the reported 2DRR shows a FoM value of 12 and a $\text{FoM}_{\text{max}}$ value of 24, one of the highest ones ever demonstrated for SHF AlN and AlScN microresonators. While we believe that a much higher $Q_m$ will be possible in the future through further design optimizations, the achievement of such an unprecedented $k^2$ makes it already possible to envision future high-order 2DRR’s based acoustic filters with a sub-3dB insertion-loss (IL) value and exhibiting an unprecedented ultra-wide BWs (~12%, see Figure 10-(a,b)). This has been further demonstrated here by designing a 50 $\Omega$-matched 5th-order 5.3 GHz 2DRR-based acoustic ladder filter, formed by resonators with the same electromechanical performance measured for the 2DRR reported in this work and by relying on a capacitance ratio ($r = C_0^a/C_0^s$, where $C_0^a$ and $C_0^s$ are the designed static capacitance of the series and shunt resonators, respectively) set to 3 (see Figure 10-(c)). As evident from Figure 10-(d), the simulated transmission ($S_{21}$) of the designed ladder filter clearly shows that the 2DRR’s electromechanical performance demonstrated in this work simultaneously enable an IL of ~2.5 dB, a BW of 11.1% and an out-of-band rejection exceeding 30 dB.

VI. CONCLUSIONS

In this Article, we reported on design, fabrication and measured performance of a Al$_{0.76}$Sc$_{0.24}$N Two-Dimensional-Resonant-Rods (2DRR) resonator exhibiting the highest electromechanical coupling coefficient ever reported for AlN or AlScN microacoustic resonant devices. The 2DRR reported here exhibits a resonance frequency of 5.31 GHz and shows a $k^2$ of 23.9%, leading to a mechanical figure-of-merit equal to 24. The ability to achieve such an extraordinary $k^2$ in a device manufacturable through CMOS-compatible fabrication processes opens unprecedented scenarios towards the development of next generation low loss ultra-wideband (UWB) SHF acoustic filters for future 5G communication systems.

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