Improving Thermal Linearity and Quality Factor of $Al_{72}Sc_{28}N$ Contour Mode Resonators Using Acoustic Metamaterials based Lateral Anchors

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ABSTRACT ***In the last years, the use of Scandium-doped AlN (AlScN) as the active material in piezoelectric resonators has been investigated by many research groups thanks to its high piezoelectric coefficients and its CMOS manufacturability. However, because of the AlScN's low thermal conductivity, any AlScN resonators inherently exhibit lower power handling than the AlN counterparts, especially when such resonators are required to be suspended in order to operate. Even more, while the adoption of larger anchors in conventional AlScN resonators enable higher power handlings, it comes with an unsustainable reduction of the resonators' quality factors (Qs). In this work, we overcome this limitation. We show that the adoption of acoustic metamaterials made of locally resonant rods at the sides of a suspended contour-mode-resonator (CMR) permits to largely increase the usable anchoring volume with respect to conventional CMR designs, enabling improved heat flows from the resonator's active to the inactive regions and, consequently, a higher thermal linearity. Furthermore, thanks to the unique dispersion features of the adopted metamaterial structure, the use of a significantly more robust anchoring strategy does not lead to any degradations of the CMR's electromechanical performance, even leading to a ~25% improvement in the measured Q.***

Keywords—AlScN, Acoustic Metamaterials, 2DRR, CMR, Thermal Conduction

I. INTRODUCTION

In the last decades, many Aluminum Nitride (AlN) acoustic resonators have been developed and used for a broad range of applications, including frequency generation, filtering and sensing **[1]**. In particular, AlN Contour Mode Resonators (CMRs) **[2]** have been studied thanks to their lithographic frequency tunability, allowing to achieve resonators with different resonance frequencies through the same CMOS compatible fabrication process. AlN CMRs are formed by two metal layers sandwiching an AlN film. They are kept attached to the substrate through two anchors placed along an in-plane direction (y) that is orthogonal to the main vibrational one (x). Such anchors must have a tiny width to prevent significant amounts of acoustic energy from leaking into the surrounding substrate, generating anchor losses and, consequently, causing reductions of the achievable quality factor (Q). Just recently, the use of Aluminum Scandium Nitride (AlScN) on behalf of AlN has been investigated to attain CMRs with higher electromechanical coupling coefficients (k_t^2) **[3]–[6]**. Nevertheless, since AlScN has a thermal conductivity that is up to two orders of magnitude lower than the one of AlN **[7]**, AlScN CMRs structurally supported by just two tiny anchors inevitably exhibit much higher thermal nonlinearities than the AlN counterparts, leading to a much lower power handling. So, it has become now fundamental to find new CMR designs suited to the adoption of AlScN rather than AlN and exploiting larger anchoring volumes without causing any Q degradations **[8]**, **[9]**.

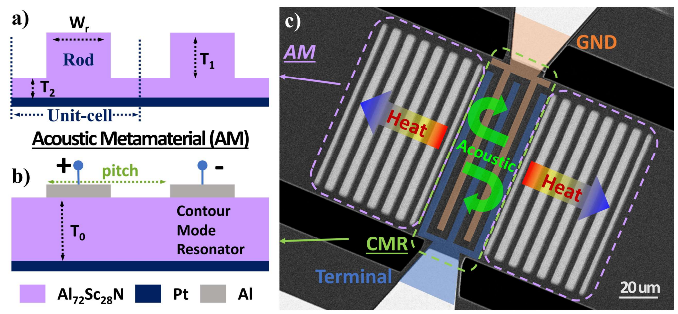

Fig. 1. A CMR design with two acoustic metamaterial structures attached along its lateral sides. (a) presents the fundamental structure of the acoustic metamaterial, which is formed by an array of unit-cells. Each unit-cell (8um in width) consists of a rod (W_r=4um, T_1=350nm) placed between two adjacent thinner (T_2=150nm) regions of the AlScN film. (b) clarifies the electrical configuration of the designed CMR, with 8um pitch and thickness of T_0 (500nm). (c) Top view of a built CMR^{AM} using two AM structures each formed by 7 unit-cells (Nu=7).

Recently, our group has reported an acoustic metamaterial (*AM*) structure based on a forest of locally resonant rods attained by corrugating thin AlN/AlScN films. When applying such AM structure in the active region of a bulk-acoustic-wave (BAW) resonator, it has led to a new class of resonators, labeled as Two-Dimensional-Resonant-Rods (2DRRs) **[10]–[15]**, with augmented k_t^2. In this work, we show that using two sets of such AM structures along the lateral sides of the active region of an $Al_{72}Sc_{28}N$ CMR, in addition to the conventional thin anchors placed along y, permits to generate an acoustic stopband preventing the piezo-generated vibration from leaking laterally, enabling even higher Qs than those attained by conventional designs with lateral sides being profiled with

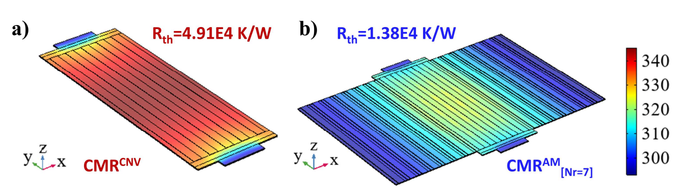

Fig. 2. FEA simulated temperature distribution for (a) CMR^{CNV} and (b) $CMR^{AM}_{[Nu=7]}$. (a) shows that the only paths for the heat flow in the CMR^{CNV} are the anchors along y, while in $CMR^{AM}_{[Nu=7]}$ the AM structures provide two further and wider paths for the heat generated during the resonator motion to flow into the surrounding substrate, resulting into a much lower temperature gradients across the resonator body. To quantify the improvement, we extracted the thermal resistance (R_{th}) of the two devices. The $CMR^{AM}_{[Nu=7]}$ shows a R_{th} (1.38E4 K/W) as *3.6* times smaller than CMR^{CNV} (4.91E4 K/W).

hard-etched sidewalls. Even more, such AM structures provide a much larger path for the heat generated in the resonator's active region during its motion to flow into the substrate, providing the means to reduce any thermal nonlinearities with respect to those affecting the performance of conventional AlScN CMRs that use only two tiny anchors along *y*.

II. Methods and Results

In order to validate the reported AlScN CMR design, we designed, built and tested six sets of lateral-field-excited (LFE) $Al_{72}Sc_{28}N$ CMRs with identical active regions and the same anchors' geometry and material composition along the *y* direction, yet employing six different lateral anchoring strategies. One configuration (CMR^{CNV}) consists in a regular CMR design (*i.e.* with lateral sides fully etched to form stress-free boundaries). One additional configuration ($CMR^{AM}_{[Nu=0]}$) was designed with a laterally un-etched AlScN plate, whereas the other four configurations ($CMR^{AM}_{[Nu=1,3,5,7]}$) were designed with AM structures along the CMRs' sides formed by 1, 3, 5 and 7 unit-cells, respectively, with identical geometry in each unit-cell. To predict the more favorable thermal behavior and the lower thermal nonlinearities enabled by the use of the designed AM structures as lateral anchors, we performed a finite element analysis (*FEA*) of CMR^{CNV} and $CMR^{AM}_{[Nu=7]}$ aiming to evaluate the maximum temperature difference across such resonators' volumes in presence of a fixed input power (*1 mW*) applied under the electrodes in their active regions. As evident, a lower temperature gradient was found in $CMR^{AM}_{[Nu=7]}$ compared to CMR^{CNV}, indicating an improved thermal conduction towards the substrate due to the adoption of the two AM structures. Even more, in order to verify that the use of such structures does not lead to any *Q* degradations, we analyzed their acoustic transmission characteristics through FEA, assuming them to be driven by a lateral and longitudinal acoustic wave. As shown in Fig. 3, we found each AM structure to exhibit an acoustic stopband between 250MHz-530MHz, i.e. in a frequency range including the expected resonance frequency of the designed CMRs. Such a unique dispersion characteristic provides the means to suppress any undesired lateral leakages of acoustic energy, hence evading any *Q* degradations.

Finally, after building all the devices, we measured their admittance responses (at least 3 per configurations) and we extracted the corresponding mechanical *Q* values (Fig. 4). As evident, the *Q* of $CMR^{AM}_{[Nu=1,3,5,7]}$ grows proportionally with the number of unit-cells, even approaching a value for $CMR^{AM}_{[Nu=7]}$ that exceeds by ~25% the *Q* of CMR^{CNV}. This proves that the use of AM structures as lateral anchors permits not only to improve the thermal characteristics of AlScN CMRs but also to augment the mechanical performance with respect to what attained in conventional designs relying on stress-free lateral sides.

III. Conclusions

In this work, we reported the first $Al_{72}Sc_{28}N$ CMRs relying on two acoustic metamaterials structures as lateral anchors along the vibrational direction. We showed that such novel anchoring strategy favors the flow of the heat generated during the motion into the substrate, paving a way towards AlScN CMRs with higher power handling. We verified that the use of such metamaterial structures also enables ~25% improved quality factors with respect to conventional CMR designs.

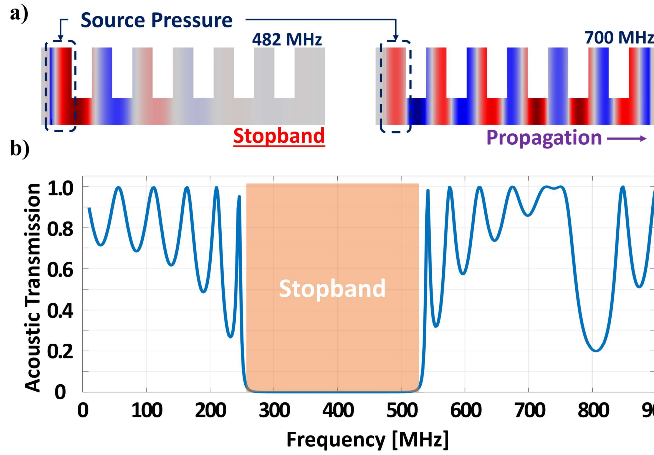

Fig. 3. FEA simulated acoustic transmission of the designed AM. (a) shows the position of the acoustic source chosen in our simulation as well as the modeshapes relative to the generated deformation within a stopband (left) and a passband (right), respectively. (b) Simulated acoustic transmission distribution *vs.* the frequency of the acoustic source adopted in our FEA.

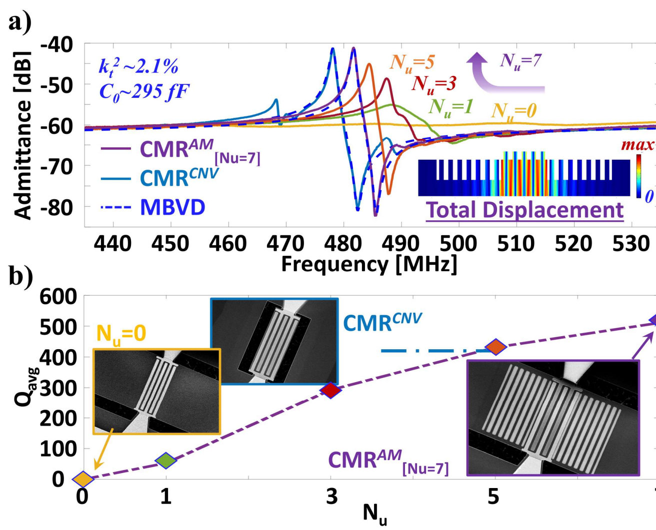

Fig. 4. (a) Measured admittance curves of the investigated designs; (b) Extracted mechanical *Q* value for all the investigated designs.

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