TOPOLOGICALLY PROTECTED FANO RESONANCE IN A 80 MHZ SC-DOPED ALN THIN FILM RESONATOR WITH A QUALITY FACTOR LARGER THAN 10K

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ABSTRACT

In this study, we introduce the first-ever AlScN resonant device able to excite a topologically protected mode of vibration. This device operates at 80 MHz, and it leverages the strong piezoelectricity of AlScN films using a 30% scandium doping concentration. By utilizing a combination of finite element simulations and experimental data, we demonstrate that the interconnection of two suspended metamaterials exhibiting distinct topological characteristics enables the generation of *localized* acoustic resonances. The destructive interference between two of these resonances creates a mechanical anti-resonance frequency with modal energy constrained within a 15 µm distance around the interface, following the physics of topologically protected Fano resonances. We show that the device's quality factor at this anti-resonance frequency reaches a value (>10,000) much higher than anything else ever reported for thin-film AlScN devices not attached on silicon, silicon carbide, or other low-loss materials. The device reported in this work opens exciting opportunities to use AlScN MEMS for sensing a variety of parameters of interest with exceptional spatial sensing resolution, sensitivity, and limit-of-detection.

Keywords: Topological Elastics, Scandium-doped Aluminum Nitride, Fano Resonance, Microelectromechanical Systems.

INTRODUCTION

Over the past fifteen years, nanoelectromechanical systems (NEMS) have emerged as key tools for analyzing biological and chemical analytes, particularly focusing on their mass properties [1,2]. Their small size, typically in the range of a few tens of micrometers, renders them capable of achieving remarkably high spatial sensing resolutions approaching the dimensions of an individual cell. However, using NEMS for sensing comes with some significant challenges. For instance, NEMS must operate in a vacuum to exhibit resonant responses with quality factors (Q) not heavily degraded by air damping. Additionally, NEMS often require nanometer-scale gaps between the electrodes used for transduction to achieve sufficient electromechanical coupling efficiency, which inevitably increases the complexity and repeatability of their fabrication process. Furthermore, the oscillator circuits used to read out the resonance frequency of NEMS consume substantial power to sustain their oscillation due to the high impedance (in the kΩ range) exhibited by NEMS at resonance.

Concurrently, microelectromechanical systems (MEMS) have also witnessed significant developments, becoming integral components in a variety of commercial electronic systems. In particular, Aluminum Scandium Nitride (AlScN) radiofrequency (RF) MEMS resonators have been playing a key role in the radios of cellular handsets. These devices excite Bulk-Acoustic-Wave (BAW) modes of vibration through the high piezoelectric coefficients of AlScN. Yet, when used as sensors, sub-1 GHz AlScN RF MEMS offer a worse spatial sensing resolution than NEMS due to their larger dimensions and wide spread of the

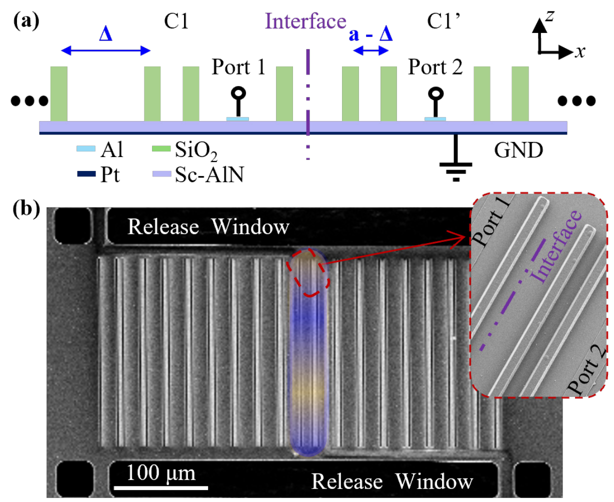

Fig. 1. (a) Cross-sectional schematic and (b) Scanned Electron Microscope (SEM) figure of the fabricated AlScN topological device reported in this work.

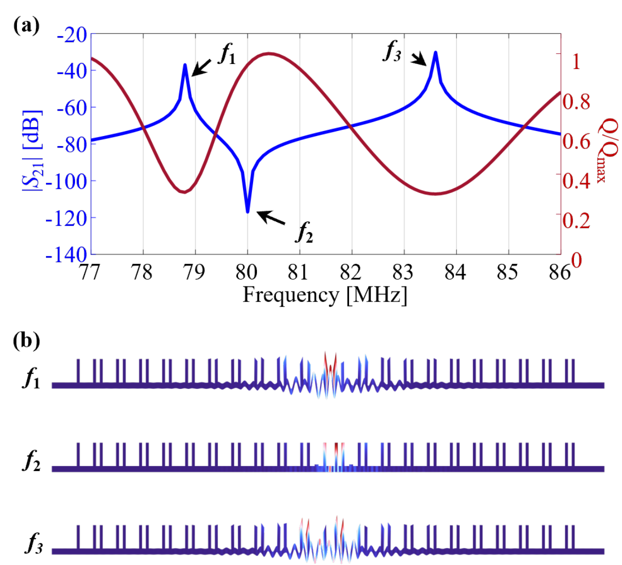

Fig. 2 (a) in blue: FEM-simulated transmission (S_{21}) of the topological device demonstrated in this work; in red: FEM-simulated quality factor associated to anchor losses vs. frequency, normalized to its maximum value; (b) Simulated total-displacement modeshapes for the reported topological device at the frequencies of the dark mode, bright mode and anti-resonance originated from the interference of dark and bright modes.

modal energy over their in-plane area. While higher frequency AlScN RF MEMS have the potential to narrow this performance

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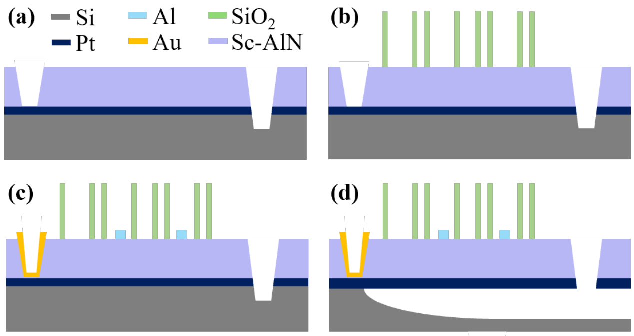

Fig. 3 The fabrication flow of the device. (a) Step 1, Pt/AlScN Deposition; 2, wet etch of AlScN for vias; 3, Pt/AlScN dry etch for release windows. (b) Step 4, SiO_2 deposition and patterning. (c) Step 5, Al deposition and lift-off; 6, Au deposition and lift-off. (d) Step 7, release the device in XeF_2.

gap with NEMS, exploiting higher frequencies comes at the expense of a lower quality factor (Q), ultimately resulting in diminished sensing sensitivity and a higher limit of detection compared to what can be achieved with NEMS.

In this work, we break all the previous paradigms and present a MEMS device able to achieve exceptionally high mode-localization and a record-high quality factor for thin-film AlScN devices. This is accomplished by exciting a topologically protected Fano resonance at the interface of two adjacent metamaterials with opposite topological invariants (i.e., Zak-phase) [3] (see Fig. 1).

RESULTS

The device discussed in this work leverages the destructive interference of two resonant states piezoelectrically excited in an acoustic bandgap, namely a *dark* mode and a *bright* mode, to excite a Fano resonance. These modes, characterized by different penetration depths along the metamaterial structures, are piezoelectrically transduced and sensed by two electrodes close to the two metamaterials' shared interface. We start by analyzing the behavior of the reported device through Finite Element Modelling (FEM). We show that the interaction of the dark mode at a frequency f_1 with the bright mode at a frequency f_3 produces a Fano resonance with an anti-resonance frequency f_2 (see the blue curve in Fig. 2-a) at which the modal energy is almost entirely localized in less than 15 µm (Fig. 2-b). As a result, a sharp notch exists in the simulated device's frequency response, between the dark and the bright modes. This notch can exhibit exceptionally high-quality factors due to its superior degree of localization and isolation from the surrounding substrate. In fact, the quality factor associated with anchor losses along the lateral direction (the x-direction shown in Fig. 1-a) is much higher at the frequency of the notch than at the resonance frequencies of dark and bright modes, as confirmed by FEM (see the red curve in Fig. 2-a).

We confirmed our simulation results by building a prototype of the reported device using a 500 nm-thick 30% scandium-doped AlN film deposited on top of an unpatterned platinum plate. The metamaterials used by this prototype rely on an array of SiO_2 rods patterned on top of the AlScN layer to alter the dispersion of the first symmetric and antisymmetric Lamb modes. Two single aluminum strips are used to form the top electrodes. More information about the fabrication process of the reported AlScN device is provided in Fig. 3. A Scanned Electron Microscope picture of the fabricated device is reported in Fig. 1-b.

We report the measured transmission (S_{21}) of the fabricated device in Fig. 4. Evidently, we found a sharp anti-resonance confined between two peaks, thereby confirming the existence of a

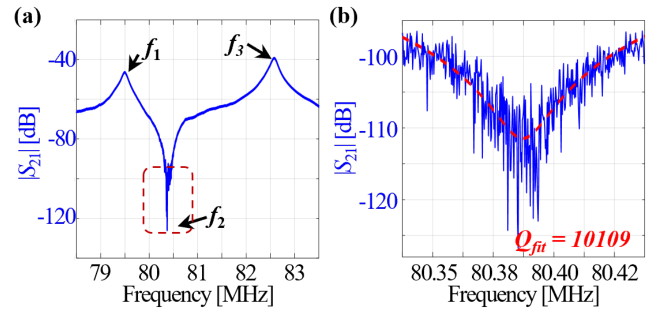

Fig.4 (a) Measured transmission (S_{21}) of the topological device demonstrated in this work (f_1, f_2 and f_3 as in the simulation curve); (b) Zoomed-in view of the transmission curve shown in a) around the anti-resonance frequency (f_2). The fitted trend we have used to extract the Q of the anti-resonance frequency from the measured data is also shown (see the red dashed line).

Fano resonance (Fig. 4-a). Also, our extracted S_{21} trend vs. frequency matches closely the simulated trend in Fig. 2-a. Thanks to its superior degree of mode localization and thanks to a cautious design of the device's supporting anchors far from the interface, the measured device's transmission exhibits a quality factor exceeding 10,000 (Fig. 4-b). This quality factor exceeds by nearly one order of magnitude what has been previously shown for conventional AlScN thin-film devices [4–10] (Table 1).

Table 1 – Qs reported in AlScN thin-film resonators.

Reference	[4]	[5]	[6]	[7]	[8]	[9]	[10]	This work
Year	2017	2018	2018	2019	2021	2022	2022	2024
f_{res} [MHz]	254	500	932	388	40	292	305	80
Q	1307	1200	1669	1658	1184	1219	1507	10109

CONCLUSIONS

We demonstrate a record-high quality factor in an RF microacoustic device using a highly-doped AlScN thin-film by piezoelectrically exciting for the first time a topologically protected Fano resonance working in the RF range. This mode also exhibits a superior degree of mode-localization. Our work brings the exotic physics of topological states of matter into the world of AlScN microsystems, giving access to properties and performance metrics that are unreachable when looking at conventional BAW modes excited in plates.

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