MICROMACHINED ALUMINUM NITRIDE ACOUSTIC RESONATORS WITH AN EPITAXIAL SILICON CARBIDE LAYER UTILIZING HIGH-ORDER LAMB WAVE MODES

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ABSTRACT

In this study, we present a composite plate composed of an aluminum nitride thin film and an epitaxial cubic silicon carbide layer has the remarkable capability to enable Lamb wave resonators with a high series resonance frequency ($f_s$) and a high quality factor ($Q$) simultaneously. The epitaxial cubic silicon carbide layer not only provides the Lamb wave resonator with low acoustic loss layers to boost the $Q$’s but also enhances the electromechanical couplings of the high-order Lamb wave modes in the composite plate. Specifically, a micromachined acoustic resonator utilizing the third quasi-symmetric (QS3) Lamb wave mode demonstrates a high acoustic velocity characteristic and a moderate electromechanical coupling [4]-[6]. However, the quality factor ($Q$) of the Lamb wave mode in an AlN thin plate is particularly preferred because it exhibits a low dispersive phase velocity characteristic and a moderate electromechanical coupling [4]-[6]. However, the quality factor ($Q$) of the Lamb wave resonator utilizing the $S_0$ mode degrades to only 500 while the resonator size is downscaled to a nanometer scale for the super-high resonance frequency up to 3 GHz [7]. Although the first symmetric ($S_1$) Lamb wave mode in an AlN thin plate demonstrates a high acoustic velocity of 26400 m/s, showing a resonance frequency up to 2.2 GHz, a $Q$ of 1100 is not satisfied [8].

So far, significant research efforts have focused on the pure AlN thin film for the designs of micromechanical electroacoustic resonators, but researchers overlooked that multiple material layers can change the acoustic wave properties and resonator performances remarkably. For example, the $Q$’s of piezoelectric thin film resonators were significantly enhanced using a substrate layer with low acoustic losses, such as single crystal silicon (Si) [9], [10].

INTRODUCTION

Piezoelectric thin films, such as zinc oxide (ZnO) and aluminum nitride (AlN), have been widely utilized in the designs of micromechanical acoustic resonators. In other words, acoustic wave propagation properties in various piezoelectric material media have been well investigated and employed in many electroacoustic resonator designs, including surface acoustic waves (SAW) [1], bulk acoustic waves (BAW) [2], and Lamb waves [3]. Recently, Lamb wave resonators have attracted great attention for the designs of micromechanical acoustic resonators as it combines the advantages of BAW and SAW: high phase velocity ($V$) and multiple frequencies ($f$) excitation by the interdigital transducers (IDT). More specifically, the lowest symmetric ($S_0$) Lamb wave mode in an AlN thin plate is particularly preferred because it exhibits a low dispersive phase velocity characteristic and a moderate electromechanical coupling [4]-[6]. However, the quality factor ($Q$) of the Lamb wave resonator utilizing the $S_0$ mode degrades to only 500 while the resonator size is downscaled to a nanometer scale for the super-high resonance frequency up to 3 GHz [7]. Although the first symmetric ($S_1$) Lamb wave mode in an AlN thin plate demonstrates a high acoustic velocity of 26400 m/s, showing a resonance frequency up to 2.2 GHz, a $Q$ of 1100 is not satisfied [8].

Figure 1: Illustration of a conventional aluminum nitride (AlN) Lamb wave resonator including an underneath layer of epitaxial cubic silicon carbide (3C–SiC).

The frequency-temperature stability of the AlN Lamb wave resonator utilizing the $S_0$ mode can be improved by adding one layer of silicon dioxide (SiO2) [11].

In this work, as shown in Figure 1, a composite layer including an AlN thin film and an epitaxial cubic silicon carbide (3C–SiC) layer is used to create high-frequency, high-$Q$, and low-impedance electroacoustic resonators utilizing high-order Lamb wave modes. The use of SiC is attractive as it has been theoretically proven to have a large $f_s Q$ product [12] due to the intrinsic low acoustic losses [13]. AlN and 3C–SiC exhibit well-matched mechanical and electrical properties which make them a suitable material combination for micromechanical electroacoustic resonators [14]. Our experimental results demonstrate that the high-order Lamb wave modes in an AlN/3C–SiC composite plate have the remarkable capability to enable high-performance micromechanical acoustic resonators. A Lamb wave resonator utilizing the third quasi-symmetric (QS3) mode exhibits a low motional impedance ($R_m$) of 91 Ω and a high $Q$ of 5510 at 2.92 GHz, demonstrating the highest $f_s Q$ product, $1.61 \times 10^{13}$ Hz, among the suspended piezoelectric thin film resonators reported to date.

LAMB WAVE MODES IN AN ALN/3C–SIC COMPOSITE PLATE

In this work, to investigate the characteristics of Lamb waves in an AlN/3C–SiC composite plate, COMSOL finite element method (FEM) multiphysics software was used to
simulate the resonance mode shapes to recognize the Lamb wave modes existing in the AlN/3C–SiC composite plate. The material constants of AlN and 3C–SiC used in the simulations are taken from the literature [15]. In general, Lamb waves only have the displacements in the $x$- and $z$-directions so that they can be classified as antisymmetric and symmetric modes according to their displacement symmetries. Antisymmetric modes have antisymmetric $x$-displacements and symmetric $z$-displacements whereas symmetric modes show symmetric $x$-displacements and antisymmetric $z$-displacements. As depicted in Figure 2(a), in a 5.1-μm-thick AlN plate, the lowest antisymmetric ($A_0$) mode shows antisymmetric $x$-displacements and the lowest symmetric ($S_0$) mode shows symmetric $x$-displacements with respect to the neutral axis.

However, the different material properties of the AlN and 3C–SiC layers make the displacements of Lamb wave modes not purely antisymmetric or symmetric with respect to the neutral axis. As shown in Figure 2(b), the first two Lamb wave modes in the composite plate are classified as the lowest quasi-antisymmetric ($QA_0$) mode and the lowest quasi-symmetric ($QS_0$) mode, respectively. As shown in Figure 3, the two-dimensional (2D) COMSOL FEM model predicts nine Lamb wave modes within a 4 GHz frequency band while the AlN and 3C–SiC thicknesses are 2.5 μm and 2.6 μm, respectively, and the wavelength is 11.08 μm. According to the displacement symmetries, the Lamb waves are separated into four QA and five QS modes in this composite structure. It should be noted that the first quasi-antisymmetric ($QA_1$) mode is missing in Figure 3 because the $QA_1$ mode theoretically has a weak coupling while the normalized AlN thickness ($h_{AlN}/\lambda$) and 3C–SiC thicknesses ($h_{3C-SiC}/\lambda$) are 0.226 and 0.235, respectively.

DEVICE FABRICATION PROCESS

In this study, the 2.6-μm-thick 3C–SiC layer was epitaxially grown on the single crystal Si (100) wafers and chemomechanically polished by NOVASiC. 2.5-μm-thick $c$-axis oriented AlN thin films were grown on the epitaxial 3C–SiC layers using alternating current (AC) reactive magnetron sputtering at approximately 350 °C [16]. The crystalline structure was determined by x-ray diffraction.
(XRD) as shown in Figure 4 where the diffraction peaks correspond to a hexagonal AlN (002) thin film, a cubic SiC (100) layer, and a cubic Si (100) substrate, respectively. The inset in Figure 4 shows that the 2.5-μm-thick AlN film has a FWHM value of 1.28°, implying the AlN film owns excellent crystallinity on the epitaxial 3C–SiC layer.

The grounded bottom electrode usually can improve the electromechanical couplings because the metallized interface strongly enhances the vertical electric field in the AlN thin film [15]. However, the electrode-to-resonator interface stress generally causes the degradation in Q’s. In order to eliminate the undesired effects caused by the bottom electrode, the AlN/3C–SiC Lamb wave resonators are intentionally designed without the metallized interface herein. Figure 5 describes the fabrication process flow used to achieve the AlN/3C–SiC Lamb wave resonators. Figure 6 shows a scanning electron microscope (SEM) image of a fabricated AlN/3C–SiC Lamb wave resonator.

EXPERIMENTAL RESULTS

The Lamb wave resonators were all tested at room temperature in air and the S_{11} parameters were measured using an Agilent E5071B network analyzer. In this work, the Lamb wave resonator has 16.5 pairs of 150-nm-thick aluminum (Al) IDT electrodes, the electrode width is 2.77 μm, and the aperture is 100 μm. As it is predicted in the COMSOL simulation, nine resonance peaks of Lamb wave modes were measured in the ultra high frequency (UHF) and super high frequency (SHF) regions. The QA_0 mode was missing in the measured results, showing agreement with the simulated results from the COMSOL FEM. Figure 7 compares the measured admittance plot of the QS_3 mode with those of the QA_0 and QS_0 modes in the AlN/3C–SiC composite plate as the lowest antisymmetric (A_0) mode and the lowest symmetric (S_0) mode in the pure AlN plate are most utilized in Lamb wave resonators. Table 1 concludes the measured performances of the QA_0, QS_0, and QS_3 Lamb wave modes for the normalized AlN and 3C–SiC thicknesses equal to 0.226 and 0.235, respectively.

Clearly, the QS_3 Lamb wave mode exhibits a large effective coupling (k^2_{eff}) of 1.2 % among the three modes discussed here. This result is similar to the S_0 mode in the pure AlN plate. In general, the S_0 mode in an AlN plate is supposed to have Q’s around 2000 [6], [8] but somehow the QS_0 mode in this composite structure shows a low Q of only 452. The reason for the degradation in Q of the QS_0 mode is still under investigation. In addition, it is worth noting that the QS_3 Lamb wave mode shows a superior characteristic in Q and an ultra-high acoustic velocity up to 32395 m/s, which is nearly three times higher than the BAW velocity (11354 m/s) in a pure AlN plate. This ultra-high phase velocity enables the Lamb wave resonator with a high resonance frequency up to 2.92 GHz even though the corresponding wavelength is as large as 11.08 μm. The ultra-high acoustic velocity also prevents the high-frequency Lamb wave resonator from the decrease in

Figure 6: Scanning electron microscope (SEM) image of a representative AlN/3C–SiC Lamb wave resonator.

Figure 7: Measured admittance plots of the Lamb wave resonator utilizing the (a) QA_0 (b) QS_0 (c) QS_3 modes in the AlN/3C–SiC composite plate. The insets are the resonance mode shapes of the corresponding Lamb wave modes.
Table 1: Comparison of the measured characteristics of the QA0, QS0, and QS3 Lamb wave modes in a AlN/3C–SiC composite plate.

<table>
<thead>
<tr>
<th>Modes</th>
<th>QA0</th>
<th>QS0</th>
<th>QS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>f₀ (MHz)</td>
<td>483.2</td>
<td>904.3</td>
<td>2923.7</td>
</tr>
<tr>
<td>Q</td>
<td>1406</td>
<td>452</td>
<td>5510</td>
</tr>
<tr>
<td>Rₚ (Ω)</td>
<td>620</td>
<td>209</td>
<td>91</td>
</tr>
<tr>
<td>k²_eff (%)</td>
<td>0.29</td>
<td>1.2</td>
<td>0.23</td>
</tr>
<tr>
<td>V (m/s)</td>
<td>5354</td>
<td>10020</td>
<td>32395</td>
</tr>
</tbody>
</table>

Q’s which is usually caused by the mechanical energy loss through the support tethers and the IDT electrode widths being downscaled to sub-micron features [7]. That is, no strict photolithography tool is needed to narrow down IDT electrode widths to achieve a GHz resonance frequency since the QS₃ mode shows an acoustic velocity exceeding 30000 m/s. Furthermore, when the wavelength of the QS₃ mode is as large as 11.08 μm, the mechanical energy loss through the support tethers can be decreased because the tether width is relatively narrower than the wavelength.

CONCLUSIONS

In conclusion, we combine a piezoelectric AlN (002) thin film with an epitaxial 3C–SiC (100) layer to enable a high-performance micromechanical resonator utilizing the QS₃ Lamb wave mode. The high acoustic velocity of the QS₃ mode boosts the resonance frequency to several GHz without strictly narrow IDT fingers and prevents the Lamb wave resonator from the decrease in Q as well since the support tethers and IDT electrodes can keep in micrometer scales when the resonator operates at the several GHz range. The experimental phase velocities of Lamb wave modes in the AlN/3C–SiC plate are in agreement with the simulated conclusions from the COMSOL FEM. Using the AlN/3C–SiC composite structure, a micromachined Lamb wave resonator utilizing the QS₃ mode exhibits a low Rₚ of 91 Ω and a high Q of 5510 at 2.92 GHz, resulting in the highest f₀/Q product, 1.61×10¹³ Hz, among all suspended piezoelectric thin film electroacoustic resonators to date.

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REFERENCES