High-\(Q\) aluminum nitride Lamb wave resonators with biconvex edges

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A Lamb wave resonator utilizing an aluminum nitride (AlN) plate with biconvex edges to enhance the quality factor (\(Q\)) is demonstrated. The simulation results based on finite element analysis verify that the use of the biconvex edges, instead of the conventional flat edges, can efficiently confine mechanical energy in the AlN Lamb wave resonator. Specifically, the measured frequency response of a 491.8-MHz AlN Lamb wave resonator with biconvex edges yields a \(Q\) of 3280 which represents a 2.6\(\times\) enhancement in \(Q\) over a 517.9-MHz Lamb wave resonator on the same AlN plate but with the suspended flat edges.

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The demand for miniaturized, low-power, low-impedance, thermally stable, and high quality factor (\(Q\)) resonators as the frequency references or band-pass filters in wireless communication systems has led current research efforts towards the integrated on-chip radio frequency (RF) front-end solutions. Among various micro-electro-mechanical resonator technologies, aluminum nitride (AlN) Lamb wave resonators utilizing the lowest symmetric (S0) mode have demonstrated the most promising technology for ultimately realizing this vision.1–5 Recently, the robust temperature compensation of AlN Lamb wave resonators by using one layer of silicon dioxide6–8 or highly doped silicon (Si)9 has been demonstrated.

However, the \(Q\)’s of the AlN-based Lamb wave resonators with a metal bottom electrode are rarely higher than 2000, and the improvement of \(Q\) is a key to achieve better performance of low-loss filters and low-phase-noise oscillators. As a result, plenty of researchers keep seeking for efficient methods to enhance the \(Q\)’s of AlN-based resonators. Abdolvand et al. proposed fabricating the AlN Lamb wave resonator on the low-loss Si substrate to enhance the \(Q\).10 Hung and Nguyen introduced a capacitive-piezoelectric transducer with small gaps between the AlN layer and the metal electrodes to boost the \(Q\) of AlN contour-mode resonator.11 Sorenson et al. used the acoustic band gap structure as the lossless support tethers to improve the \(Q\) of AlN/Si Lamb wave resonator.12 In addition, since silicon carbide (SiC) has a very high acoustic velocity and a low acoustic loss,13 the AlN/SiC composite layer has been used to enhance the \(Q\)’s of AlN-based resonators as well.14–16 The present work demonstrates that the suspended biconvex edges can efficiently reflect the Lamb waves back towards the center of the AlN Lamb wave resonator as well as confine the displacement and the mechanical energy in the resonator. Accordingly, the energy dissipation through the support tethers is significantly minimized to enhance the \(Q\).

As illustrated in Fig. 1(a), a conventional Lamb wave resonator consists of one interdigital transducer (IDT) and one grounded bottom electrode on the opposite sides of an AlN plate with suspended flat edges. The simulation from COMSOL finite element analysis (FEA) depicts the resonance mode shape of the AlN Lamb wave resonator with flat edges as shown in Fig. 1(b). Obviously, the displacement occurring in the support tethers implies that a part of acoustic energy is lost through the tethers even though the tether lengths have been designed as an odd multiple of a quarter-wavelength. Moreover, because most surfaces of the AlN Lamb wave resonator are in contact with air and there is a large acoustic mismatch between the AlN and air, a very small amount of Lamb wave energy is transmitted into air. Hence, the mechanical energy loss through the support...

\(\text{FIG. 1. (Color online) (a) Illustration and (b) resonance mode shape (displacement profile) of a conventional AlN Lamb wave resonator with flat edges. (c) Illustration and (d) resonance mode shape (displacement profile) of an AlN Lamb wave resonator with biconvex edges.}\)
tethers would definitely dominate the decrease of $Q$, especially for Lamb wave resonators operating at high frequencies.

It is known that the biconvex shape has been applied to quartz resonators to trap mechanical energy in the center and reduce the energy dissipation at the edges. In this letter, adopting a similar concept for the design of Lamb wave resonators, the biconvex shape is implemented into the lateral direction to trap the mechanical energy in the resonator to enhance the $Q$. As illustrated in Fig. 1(c), an AlN Lamb wave resonator is composed of the same IDT electrode configuration as Fig. 1(a) but with the biconvex shape in the both lateral edges. Figure 1(d) pictures the resonance mode shape of the AlN Lamb wave resonator with biconvex edges. Due to the biconvex shape, the displacement is mostly confined in the center of the Lamb wave resonator and only little displacement occurs in the support tethers, which indicates that very little energy dissipates through the tethers and accordingly higher $Q$’s can be attained.

To study the effect of edge shape on $Q$’s, Lamb wave resonators based on the AlN plates utilizing the suspended flat, biconvex, and biconcave edges with various radii of curvature are designed. The design parameters are summarized and listed in Table I. In order to minimize the experimental errors resulting from the fabrication processes, all the resonators were fabricated on the same wafer and placed in the same vicinity. The AlN Lamb wave resonators were all tested in air and $S_{11}$ parameters were extracted using an Agilent E5071B network analyzer. The measured $Q$ was extracted from the admittance plot by dividing the series resonance frequency ($f_s$) by the 3 dB bandwidth. In addition, the effective coupling coefficient ($k_{\text{eff}}^2$) of the measured devices is defined as

$$k_{\text{eff}}^2 = \frac{\pi f_s}{2 f_p} \left[ \tan \left( \frac{\pi f_s}{2 f_p} \right) \right]^{-1},$$

where $f_s$ and $f_p$ are the series resonance frequency and parallel resonance frequency, respectively.

Figure 2 presents the measured frequency characteristics for the Lamb wave resonators on a 1.5-$\mu$m-thick AlN plate utilizing the flat edges and the biconvex edges with a curvature radius $R$ of 209.2 $\mu$m, showing $Q$’s of 1255 and 3280, respectively. The measured $Q$ of the AlN Lamb wave resonator with biconvex edges represents a 2.6X increase in $Q$ over the resonator with flat edges. Moreover, the resonator with biconvex edges shows a lower motional resistance ($R_m$) than that with flat edges. The $R_m$ is 364 $\Omega$ for the resonator with biconvex edges and the $R_m$ equals 395 $\Omega$ for that with flat edges. Figure 3 compares the measured $Q$’s for the AlN Lamb wave resonators using the biconvex edges with various radii of curvature equal to 209.2 $\mu$m, 302.3 $\mu$m, and 493.8 $\mu$m, resulting in $Q$’s of 3280, 2932, and 3196, respectively. Compared with the flat edges, the biconvex edges can efficiently confine the mechanical energy in the resonator and reduce the energy dissipation occurring in the support tethers so that the $Q$ can be significantly boosted.

However, as depicted in Fig. 3, the resonator with flat edges shows a $k_{\text{eff}}^2$ of 0.35% and the resonators utilizing the biconvex edges with various radii of curvature equal to 209.2 $\mu$m, 302.3 $\mu$m, and 493.8 $\mu$m, exhibiting the $k_{\text{eff}}^2$ of 0.18%, 0.2%, and 0.24%, respectively. Clearly, the energy confinement using biconvex edges reduces the $k_{\text{eff}}^2$ because the side parts of the IDT do not excite the resonance mode. The resonators studied in this work have $Q$’s that are

<table>
<thead>
<tr>
<th>Table I. Geometric dimensions of Lamb wave resonators.</th>
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<tr>
<td>IDT electrode number</td>
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<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Aperture ($\mu$m)</td>
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<tr>
<td>Pt electrode thickness (nm)</td>
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<tr>
<td>Radius of curvature, $R$ ($\mu$m)</td>
</tr>
<tr>
<td>AlN plate length ($\mu$m)</td>
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<tr>
<td>AlN plate width ($\mu$m)</td>
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<td>AlN plate thickness ($\mu$m)</td>
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FIG. 3. (Color online) Comparison of measured $Q$’s and effective coupling coefficients of the AlN Lamb wave resonators with the flat edges and the biconvex edges with various radii of curvature. Inset is the illustration of the dimensions of the resonator with biconvex edges.
Furthermore, the floating bottom electrode configuration could be further optimized to increase the $Q$. It should be noted that the $Q$ increases from 4.4 to 7.7 simply through the use of biconvex curvature. In addition, the $Q$ and $k^2_{\text{eff}}$ reported in this work are not optimal by far. The radius of curvature and the ratio of the AlN thickness to wavelength could be further optimized to increase the $Q \cdot k^2_{\text{eff}}$ product. Furthermore, the floating bottom electrode configuration could be employed in the resonator design to improve the $Q \cdot k^2_{\text{eff}}$ product.

In contrast to the biconvex edges, as shown in Fig. 4, the AlN Lamb wave resonators using the biconcave edges with various radii of curvature do not show any large resonance peak in the measured frequency responses. Apparently, the suspended biconcave edges disperse the Lamb waves and then the degradation of the resonance peak is induced by the leakage of mechanical energy through the support tethers. In addition to $Q$, the frequency-temperature behavior of the AlN Lamb wave resonators is of interest. In this work, the room temperature ($25 \, ^\circ C$) is used as the reference temperature to study the frequency-temperature behavior of the resonators. As illustrated in Fig. 5, the Lamb wave resonators on the 1.5-$\mu m$-thick AlN plate utilizing the flat edges and the biconvex edges with a curvature radius of 209.2 $\mu m$ show the first-order temperature coefficient of frequency (TCF) of $-22.5 \, ppm/\, ^\circ C$ and $-22.4 \, ppm/\, ^\circ C$, respectively. The resonators exhibit almost the same first-order TCF because they are composed of the same material stack and employ the same $S_0$ mode Lamb wave.

In summary, this work demonstrates a 491.8-MHz Lamb wave resonator on a 1.5-$\mu m$-thick AlN plate utilizing the biconvex edges with a curvature radius of 209.2 $\mu m$ yields $Q$ as high as 3280 which represents a 2.6$	imes$ enhancement in $Q$ over a 517.9-MHz Lamb wave resonator with flat edges. The experimental results confirm the FEA simulations that the suspended biconcave edges can efficiently confine mechanical energy in the Lamb wave resonator and reduce the energy dissipation through the support tethers. Accordingly, the $Q$ of the AlN Lamb wave resonator can be significantly boosted by using the biconvex edges.

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$Q \cdot k^2_{\text{eff}}$ product can be increased from 4.4 to 7.7 simply through the use of biconvex edges with a larger radius of curvature (493.8 $\mu m$). However, it should be noted that the $Q$ may decrease as the radius of curvature is increased significantly. In addition, the $Q$ and $k^2_{\text{eff}}$ reported in this work are not optimal by far. The radius of curvature and the ratio of the AlN thickness to wavelength could be further optimized to increase the $Q \cdot k^2_{\text{eff}}$ product.

In summary, this work demonstrates a 491.8-MHz Lamb wave resonator on a single 1.5-$\mu m$-thick AlN plate utilizing the biconvex edges with a curvature radius of 209.2 $\mu m$ yields a $Q$ as high as 3280 which represents a 2.6$	imes$ enhancement in $Q$ over a 517.9-MHz Lamb wave resonator with flat edges. The experimental results confirm the FEA simulations that the suspended biconcave edges can efficiently confine mechanical energy in the Lamb wave resonator and reduce the energy dissipation through the support tethers. Accordingly, the $Q$ of the AlN Lamb wave resonator can be significantly boosted by using the biconvex edges.

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