High Quality Factor Surface Fabry-Perot Cavity of Acoustic Waves

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Surface acoustic wave (SAW) resonators are critical components in wireless communications and many sensing applications. They have also recently emerged as subject of study in quantum acoustics at the single phonon level. Acoustic loss reduction and mode confinement are key performance factors in SAW resonators. Here we report the design and experimental realization of a high quality factor Fabry-Perot SAW resonators formed in between tapered phononic crystal mirrors patterned on a GaN-on-sapphire material platform. The fabricated SAW resonators are characterized by both electrical network analyzer and optical heterodyne vibrometer. We observed standing Rayleigh wave inside the cavity, with an intrinsic quality factor exceeding $1.3 \times 10^7$ at ambient conditions.

I. INTRODUCTION

In last decades, surface acoustic wave (SAW) devices have found wide use in analog signal processing [1, 2], wireless communications [3, 4] and a range of sensing applications [5, 6]. Recently, SAW based quantum acoustics have received considerable attention for their flexibility in coupling with various quantum systems, including the superconducting qubits [7, 8], NV centers in diamond [9], quantum dots [10], and is potential for building hybrid quantum networks [11]. Despite their significance in classical and quantum information processing, achieving low loss resonator and efficient mode confinement are still challenging.

By analogy to optics, an acoustic resonator can be constructed in the form of Fabry-Perot (FP) cavity in which the SAW is bounced between two mirrors and confined in between. Unlike optics where highly reflective mirrors can be patterned from a high-refractive-index waveguiding layer, unsuspended, directly etched acoustic reflectors are often insufficient in producing high enough reflectivity to prevent coupling to bulk acoustic modes [12]. By shorting interdigital transducers (IDT), the SAW can be confined more gently because of the small velocity contrast between the region with and without metal cladding [13]. This gentle confinement however requires a large number of IDTs and hence very large device area for high reflectivity which in turn could cause SAW suffering from the Ohmic loss of the metal, leading to limited quality factor. Recently, such FP type SAW resonators have been demonstrated in the context of quantum acoustics utilizing superconducting electrodes, with Q reaching 0.5 million but the devices are limited to operate only at cryogenic temperatures [14].

Recently it was shown that it is feasible to confine SAW with phononic band gap structures [15, 16]. Challenges remain in achieving full acoustic confinement and bringing the quality factor of such acoustic resonators to the value of their suspended counter part, which is fragile and requires micromachining processing. Here we report a SAW FP cavity formed by surface patterned phononic crystal (PnC) mirrors which provide high reflectivity with a much reduced mirror length, thus enabling high-Q room temperature SAW resonators. By harnessing the engineered band gap of phononic structure [17, 18], we design the cavity for the Rayleigh surface modes. The device is fabricated by GaN-on-sapphire material system, and the cavity modes are excited by intra-cavity IDTs. The microwave reflection spectrum shows very high Q resonances with predicted free spectral range (FSR), indicating the strong confinement of SAW modes and enhanced coupling to the IDTs. In addition, the cavity acoustic field is also probed by a custom-built optical vibrometer, allowing for the identification of the confined SAW modes. The demonstrated devices pave a new direction for the study of strong phonon-matter interaction as an analogue to the cavity quantum electrodynamics [22] and the cavity optomechanics [23].

II. DESIGN

The acoustic FP resonators are patterned from Gallium Nitride (GaN) (0001) epitaxially grown on c-plane sapphire substrate [24]. GaN is a piezoelectric material with low mechanical damping [25]. Due to its lower acoustic shear velocity than that of the sapphire substrate, the acoustic waves can be guided by the GaN layer, where an acoustic cavity can be further formed by lateral confinement through a pair of PnC acoustic mirrors, schematically shown in Fig. 1(a). IDTs are directly placed within the cavity atop the GaN layer to excite SAW. At cavity resonances, standing waves are built-up within the excitation bandwidth of the IDTs. Within the cavity, the coupling between acoustic waves and the IDTs are enhanced and therefore the number of IDT electrodes can be minimized (5 pairs are utilized in a typical device).

To avoid the scattering loss to the substrate, we adapted a tapered mirror design which is first proposed in Ref. [19] for achieving efficient acoustic wave transitions in the phononic crystals.

The unit cell of the PnC structure, a square pillar with
Figure 1. (a) Schematic illustration of acoustic Fabry-Perot cavity design where the SAW is confined by a pair of square lattices PnC mirror and excited by IDTs. (b) The dispersion of Rayleigh and Love mode without PnC. The unit cell is set to have a period of $a = 11 \mu m$ and thickness of $b = 5 \mu m$. (c) The phononic band structures of GaN-on-sapphire square PnC with elliptical hole in each unit cell. The unit cell is shown as inset and $a$, $b$, $r_1$, $r_2$ represent the period of square lattice, the thickness of GaN, the major and minor radius of elliptical hole, respectively. Different colors represent different groups of modes in PnC unit cell: red and yellow modes have dominant out-of-plane displacement; blue and green modes have dominant in-plane displacement. (d) Simulated displacement profile of Love mode in the SAW cavity. (e) Simulated displacement profile of Rayleigh mode in the SAW cavity.

III. FABRICATION AND CHARACTERIZATION

The device fabrication starts from the growth of 5 $\mu m$ GaN on c-plane sapphire wafers by metal-organic chemical vapour deposition (MOCVD) [24]. To fabricate the PnC resonator, a 1.2 $\mu m$ layer of SiO$_2$ is deposited with plasma-enhanced chemical vapor depo-
could be estimated by spectral range (FSR) of 3.25 MHz. The bandwidth of IDTs ricerated SAW cavity indicates high Q resonances with a free the SAW cavity. (b) Microwave reflection spectrum of fab-(top view) with 100 periods of elliptical holes on each side of Figure 2. (a) SEM image of a fabricated PnC SAW resonator (top view) with 100 periods of elliptical holes on each side of the SAW cavity. (b) Microwave reflection spectrum of fabricated SAW cavity indicates high Q resonances with a free spectral range (FSR) of 3.25 MHz. The bandwidth of IDTs could be estimated by \(f_0/2N \sim 20\) MHz. Insets show the zoom in spectrum (symbols) of an acoustic mode with highest quality factor (left inset) and another acoustic mode with largest extinction ratio (right inset) fitted by a Lorentz function.

sition (PECVD). The PnC structures are patterned with electron beam lithography (EBL) using polymethyl methacrylate (PMMA) resist, followed by a lift-off process to deposit a 40 nm thin layer of chromium. After lift-off, the pattern are transferred to SiO\(_2\) layer by florine-based reactive ion-etching (RIE), then subsequently transferred to GaN layer by chlorine-based RIE. A second EBL process is carried on using a bi-layer PMMA resist to deposit the IDTs by a lift-off process (50 nm chromium and 50 nm gold).

A scanning electron microscope (SEM) image of the fabricated device is shown in Fig. 2(a). The size of cavity regime is 1.1 mm wide (in y direction) and 0.5 mm long (in x direction), with a pair of PnC mirrors on the ends of cavity. Each mirror contains a square lattice PnC with 100 \(\times\) 100 elliptical holes whose dimensions are identical with the simulation. The inset shows the first eight columns of PnC holes. A chip with several fabricated devices is placed on a printed circuit board (PCB) with SMA connectors and wire bonded for the electrical characterization.

The reflection spectrum around the working frequency of the resonator is recorded with a vector network analyzer. As shown in Fig. 2(b), a series of Lorentzian-shaped dips is clearly observed, indicating a group of well confined resonance modes supported in the cavity. All modes share an approximately same free spectral range (around 3.25 MHz, as marked in the figure), suggesting that they have similar group velocities but the modes within one FSR should have different modal profiles. Based on group veolcity of Rayleigh mode (the confirmation of mode type is made through vibrometer measurement and will be discussed later) \(v_R = 4705.8\) m/s from simulation, the effective cavity length \(L = 724\) \(\mu\)m could be estimated as \(\text{FSR} = v_R/2L\), which matches well with the vibrometer measurement. We attribute the resonances between each pair of main resonance dips to high-order modes along the thickness direction. They have lower extinction ratios comparing to main resonances since the coupling between these modes and IDTs is relatively weak. Lorentzian fitting is then applied to all mode. The resonance with highest quality factor has a central frequency of 192.52 MHz, with a loaded Q of \(1.37 \times 10^4\). Because all the modes are weakly coupled to the external circuit, the intrinsic Q is nearly the same with loaded Q. This quality factor is more than one order of magnitude larger than the previous work on GaN SAW resonator, while the \(f \times Q\) product (\(\sim 2.7 \times 10^{12}\)) is improved by a factor of three \(16\) and becomes comparable to the suspended GaN PnC resonators \(27\). Nevertheless, this measured \(f \times Q\) is still below the theoretical prediction \(25\), suggesting we have not yet reached the material limited quality factor. The quality factor can be further improved by further reducing the radiation and the metal losses, for example, by increasing the cavity length in y direction or by eliminating the radiation loss at IDT-electrode interfaces.

The resonance at \(f_0 \approx 194.07\) MHz, on the other hand, have the largest extinction ratio among all observed modes and is selected to analyze the coupling efficiency between IDTs and SAW. According to input-output formula \(28\), the amplitude reflection of a cavity could be written as

\[
\mathcal{R} = \frac{\kappa_{\text{int}} - \kappa_{\text{ext}} - 2i\Delta}{\kappa_{\text{int}} + \kappa_{\text{ext}} - 2i\Delta}
\]

where \(\Delta = \omega - \omega_0\) is the frequency detuning from the resonance frequency, and \(\kappa_{\text{int}}, \kappa_{\text{ext}}\) are the internal and external coupling coefficient. In our case, \(\kappa_{\text{int}} = 2\pi f_0/Q_{\text{int}}\) represents the intrinsic loss in cavity (including all the losses except the loss to microwave channel), \(\kappa_{\text{ext}}\) describes the coupling strength between microwave and SAW through the IDTs. The value of internal and external coupling coefficient could be extracted from the Lorentzian fitting: \(\kappa_{\text{int}}/2\pi = 26.3\) kHz , \(\kappa_{\text{ext}}/2\pi =\)
If we consider the IDTs at resonance frequency as a lumped element in transmission line, the amplitude reflection is $R = (Z_{\text{eff}} - Z_0)/(Z_{\text{eff}} + Z_0)$, where $Z_0 = 50 \, \Omega$ is the characteristic source impedance and $Z_{\text{eff}}$ is the effective impedance of IDT and resonator. If $\kappa_{\text{int}}$ and $Z_0$ are fixed, we have $\kappa_{\text{ext}} \propto 1/Z_{\text{eff}}$. Here $Z_{\text{eff}}$ is found to be $2.87 \, k\Omega$. Since the IDTs should be effectively considered as parallel connected component in circuit, the external coupling coefficient $\kappa_{\text{ext}}$ is proportional to the area of IDTs. By further increasing the area of IDTs, a critical coupling between microwave and acoustic cavity could be reached. In this work 5 pairs of IDT fingers are sufficient to excite SAW.

A custom-built optical heterodyne vibrometer [29] is then applied to assess and identify the modal profile of the resonator. A simplified scheme of the optical heterodyne vibrometer is shown in Fig. 3(a). The mode with central frequency of $194.07 \, MHz$ with largest extinction is chosen to be the imaged. Due to the limited field of view of the vibrometer, we select three different scan locations to assess the vibration mode: a square near the center of cavity (red box in Fig. 3(b)), a line scan inside the cavity (blue line) and a line scan extending outside the cavity into the PnC mirror along x axis (yellow line). The measurement results are shown in Figs. 3(c), (d) and (e) respectively. From Figs. 3(c) and (d), we confirm that a well confined Rayleigh mode with sinusoidal out-of-plane displacement is obtained. Love mode have not been observed under the vibrometer, due to the low excitation efficiency of IDTs for Love mode. And Fig. 3(e) shows a smooth and fast attenuation of z direction displacement amplitude after the acoustic wave enters PnC regime, indicating that 100 periods of elliptical holes we use is redundant. A PnC mirror with 20 periods of PnC holes would be sufficient to confine high Q acoustic mode within the cavity, reducing the mirror length to less than $220 \, \mu m$.

**IV. CONCLUSION**

In conclusion, we have designed and fabricated high-Q SAW Fabry-Perot resonators at the frequency around $200 \, MHz$, with highest Q-factor about $1.3 \times 10^4$. Through vibrometer measurement, confined Rayleigh mode is directly visualized inside the cavity and evanescent wave observed at the phononic crystal mirror. Our approach can also be extended to other frequencies and may achieve even higher Q, particularly at cryogenic temperatures or with other materials. The demonstrated high-Q resonator is compatible with the sensing applications (such as mass sensor [30] and gyroscope [31]) and also is promising for the study of strong phonon-matter interaction, especially when the device is advanced to operate at tens of GHz under cryogenic condition.

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