TAPERED PHONONIC CRYSTAL SAW RESONATOR IN GAN

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ABSTRACT

This paper presents a new Phononic Crystal (PnC) resonator design in which a tapered PnC is used to confine a 970 MHz SAW resonance in a GaN-on-Si platform. Like other SAW resonator designs, the proposed resonator eliminates the release step common to most MEMS devices, leading to higher yield and simpler design and packaging.

However, the use of a tapered PnC reflector in this work (Fig. 1) reduces the footprint of SAW resonators by $> 100\times$ relative to conventional metal grating reflectors while maintaining high Q. A $3.5\times$ improvement in Q is experimentally demonstrated relative to resonators with uniform PnC reflectors of comparable dimensions. These devices can be integrated seamlessly with GaN MMIC technology.

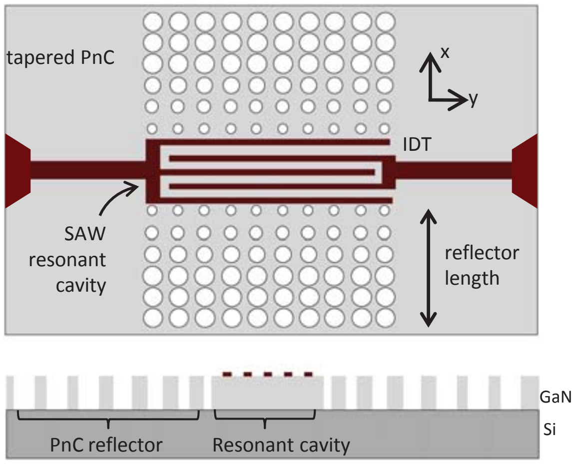

Figure 1: Top view and cross section schematics of tapered Phononic Crystal (PnC) SAW resonator.

INTRODUCTION

GaN MEMS resonators benefit from high piezoelectric coefficients, low acoustic losses, high electron mobility, radiation hardness, 2D electron gas (2DEG) sensing and transducer switching [1], and capacity for monolithic integration with HEMTs and passives in GaN MMIC technology [2]. In particular, many groups have studied GaN SAW devices for sensors and RF front-end components due to ease of fabrication on multiple substrates (e.g. SiC, Sapphire). However, one drawback of conventional SAW resonators is their large size, limited by low acoustic impedance mismatch of periodic metal gratings used to confine acoustic energy. Typically, hundreds of gratings are required, resulting in mm-scale devices. Shallow grooves (depth $h \ll \lambda_{SAW}$) etched into the piezoelectric material can increase acoustic impedance mismatch with 2-3$\times$ reduction in footprint. In principle, deep etched grooves would provide stronger reflection, but resonance degrades rapidly with groove depth for $h/\lambda_{SAW} > 0.025$ due to wave scattering into the substrate [3].

Alternately, a Phononic Crystal (PnC) composed of deep etched periodic holes can be implemented to form the SAW reflector. Such micro-scale PnC structures have been shown to provide good acoustic confinement [4]. Researchers have demonstrated PnCs in metal gratings [5] and band gaps for SAWs using etched holes [6]. However, just as in the case of deep-etched groove reflectors, a deep-etched uniform PnC provides too high an impedance contrast to the resonant cavity, resulting in substrate scattering at the resonator-PnC interface (Fig. 2(a)). In this work, we modify the PnC reflector to generate a gradual impedance change using tapered hole dimensions and reduce SAW scattering at the resonator boundaries (Fig. 2(b)). As can be seen, only 20 layers of reflectors are necessary for effective energy confinement, leading to SAW resonator design with significantly smaller footprint. This tapered PnC is analogous to Gradient Index (GRIN) photonic crystals. This method of tapering reflectors cannot be applied to deep-etched grooves, since the very first free boundary will prevent acoustic waves from penetrating through, thus no subsequent tapering structures are of any effect.

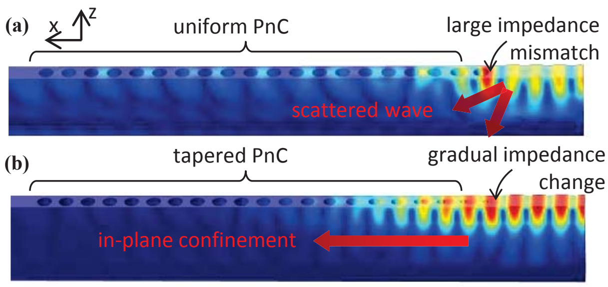

Figure 2: Simulation of SAW resonators with (a) uniform PnC reflector and (b) tapered PnC reflectors. The tapered design eliminates scattering of the SAW wave into the substrate due to abrupt acoustic impedance mismatch.

DESIGN AND SIMULATION

A square lattice PnC was chosen to form reflectors for the SAW resonator and to provide a band gap for effective confinement of acoustic energy. The PnC unit cell is a square pillar of infinite height composed of 1.56μm of GaN and infinite Si substrate underneath. A circular void is etched through the GaN layer from the top, providing scattering and reflection for the incoming SAW wave. The PnC band structure (or, dispersion relationship) of the unit cell is given in Fig. 3(a) and the irreducible Brillouin zone (IBZ) is shown in Fig. 3(b).

The band structure was derived in COMSOL FEM simulation by calculating the eigenfrequencies of the unit cell for each specific wave vector k, which is applied as a Floquet periodic boundary condition. In simulation, the unit cell is made tall enough (in the z-axis) to imitate the behavior of an infinite pillar. It has been verified that increasing the unit cell height does not affect bands below the sound cone, which contains an infinite number of modes that propagate in the Si substrate. The first 25 eigenmodes were calculated at each k to determine the PnC dispersion relations as shown in Fig. 3(a). Both modes outside the sound cone and modes populating the sound cone can be seen.

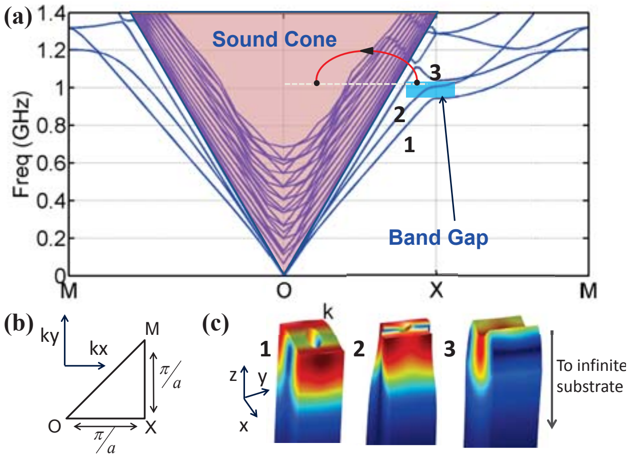

Figure 3: (a) Band structure of the PnC unit cell ,(b) its irreducible Brillouin Zone and (c) mode shapes for the 3 most relevant modes falling outside the sound cone, which do not propagate in the Si substrate.

It should be noted that the PnC does not have a complete band gap across all wave propagation directions (k). Rather, there is only partial band gap (between band 3 and band 1) from O to X. Band 2 cuts across the gap, but its displacement field is mostly along y-axis, as opposed to bands 1 and 3 whose displacement fields are along the x-axis and z-axis, as shown in Fig. 3(c). As a result the SAW wave propagating along the x-axis cannot couple with band 2. This partial band gap is sufficient for the designed resonator since the PnC needs to be reflective only in the resonant dimension and the targeted 1GHz resonance is located in the middle of the gap. If the PnC were directly applied to define the resonator boundaries, there would be an abrupt transition from solid GaN to PnC reflector resulting in broken translational symmetry along the x-axis. This would result in a coupling of modes between those in the PnC band gap and the infinite number of modes inside the sound cone, causing scattering into the substrate (illustrated in Fig. 3(a) using the red curve). The tapered PnC provides an adiabatic change in acoustic impedance such that the SAW propagates only in plane. This condition reduces scattering and isolates the surface modes from those of the sound cone.

Table 1 tabulates the performance of SAW resonators using various reflector designs for comparison with the proposed tapered PnC resonator. A figure of merit (FOM) of $f \cdot Q/L'$ is defined to capture the trade-off between reflector size and performance. Here L' is the reflector length normalized by $\lambda_{SAW}/2$. The 1GHz tapered PnC design in

SAW Reflector	f (MHz)	Q	L'	FOM	Comment	
Metal grating	34.6	3850	400	333	Al on $LiNbO_3$ [8]	
Shallow etched grating (grooves)	170	12000	300	6840	Y-Z $LiNbO_3$ [3]	
	174	30000	600	8700	Y-Z $LiNbO_3$ [3]	
	175	30000	600	8750	ST-quartz [3]	
	786	11250	1000	8843	rotated Y-cut quartz [7]	
Deep etched uniform PnC	980	246	20	12054	1.56um GaN on Si (simulation)	this work
Deep etched tapered PnC	979	2600	20	1.27e5	1.56um GaN on Si (simulation)	

Table 1: Comparison of SAW resonator performance. FOM is defined as $f \cdot Q/L'$, where L' is reflector length normalized by $\lambda_{SAW}/2$.

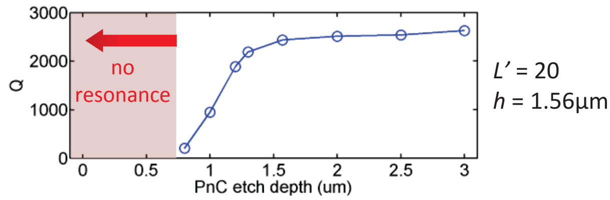

Figure 4: Simulated dependence of Q on etch depth of a 1 GHz SAW resonator with tapered PnC reflectors in GaN on (111) Si.

GaN-on-Si exhibits 14× higher FOM than state of the art Quartz [7][3] and LiNbO3 [8][3] SAW resonators. This result is based on FEM simulation assuming 1.56μm GaN on (111) Si with PnC etched through the GaN layer. The quality factor extracted from FEM modeling is due to substrate losses simulated through Perfectly Matched Layers (PMLs). In the case of the tapered PnC, a fixed PnC pitch was used while hole diameter was varied linearly to adjust the local acoustic impedance in the PnC. A maximum hole radius of $r = 0.21 \times a$ (where a is the PnC pitch) was chosen based on lithography and etching limitation for microfabrication. Unlike the case of etched grooves and uniform PnC, a deeper etch does not necessarily result in more scattering, since we can achieve an adiabatic impedance change between the resonant cavity and the reflector using varying hole dimensions. The tapering structure does lead to a slight increase in the total footprint, but this price is insignificant compared to the drastic increase in Q compared with the uniform PnC or the hundreds of reflecting grooves in conventional SAW resonators.

As seen in Fig.4, simulated Q for the tapered PnC resonator increases with etch depth, but saturates at depths $h \sim \lambda_{SAW}$. However there are practical constraints on the etch depth defined by fabrication limitations. Correspondingly, a minimum hole size of 0.3μm and linear taper over 8 unit cells were chosen for 1GHz SAW design (pitch a = 1.92μm, max hole diameter = 0.81μm). The devices in this work are based on a design with etch depth of 1.56μm.

In practice, it is expected that etch depth will be affected by the hole diameter. As the voids become smaller, the etch will be shallower and thus non-uniform along the tapered PnC. However, the tapered SAW resonator design is robust to the etch depth and hole size correlation, since all that is required is an adiabatic transition from homogeneous material to uniform PnC reflectors. A gradual transition that involves both growing hole diameter and deeper etch achieves this goal and can be optimized by adjustment of PnC tapering to compensate for any effect of reduced etch depth for smaller hole size.

FABRICATION

Folded PnC resonators were fabricated in MIT's Microsystems Technology Lab using Raytheon's MMIC GaN-on-Si heterostructure, comprised of AlGaN(25 nm)/GaN(1.7 μm) grown on (111)-Si using Molecular Beam Epitaxy (MBE).

A shallow AlGaN etch was used to remove the 2D electron gas (2DEG) between the Al-GaN/GaN layers and allow for efficient piezoelectric transduction in the GaN layer. A 100 nm layer of Ni (which can be used as the gate metal for GaN HEMTs) was then deposited and patterned to define piezoelectric IDTs. The choice of Ni for the electrodes is a departure from conventional Au electrodes found in GaN MMICs, as Au is mechanically lossy and is known to reduce resonator Q. However, Au-free GaN HEMT technology is starting to become mainstream as foundries develop heterogeneous processes with CMOS or simply want to run GaN processes in the same facilities as CMOS. Since these devices are processed side by side with GaN HEMTs, a PECVD Si_3N_4 layer (150 nm) was deposited to passivate the surface and protect the 2DEG channel in the HEMTs. A deep Cl_2 GaN etch then defined the PnCs and acoustic cavities.

Metal pads (50 nm Ti/300 nm Au) were then connected to the gate electrodes through vias in the passivation layer. In our typical GaN MEMS processing [1], a XeF_2 etch would then be used to release the MEMS structures from the Si substrate. This step is not necessary for SAW devices. Fig. 5 shows the device cross section.

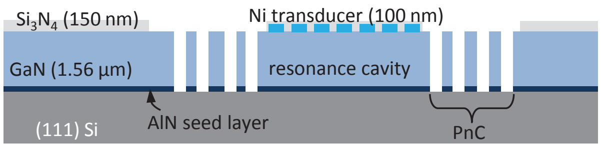

Figure 5: Cross section of the fabricated GaN SAW resonator using MBE GaN on (111) Si.

RESULTS AND ANALYSIS

Devices were characterized in vacuum using a standard 1-port measurement using an Agilent 5225A Network Analyzer, with on-chip Open de-embedding. SEMs for GaN SAW resonators with metal grating, uniform PnC, and tapered PnC reflectors, along with their measured frequency response are shown in Fig. 6. All three resonators have identical overall dimensions ($L' = 20$). The metal grating SAW resonator shows no discernable peak as the dimension of the reflector is too small to successfully confine a mode. The uniform PnC provides Q of 248 at 947 MHz. In comparison, the tapered PnC resonator demonstrates Q of 880 at 976 MHz, a 3.5$\times$ improvement in performance. Measured Q is lower than predicted by simulation due to exposure and etch variations resulting in smaller and shallower holes in the PnC than designed. However the comparison between the different resonator designs on the same chip clearly demonstrates the benefits of tapered PnC design over uniform PnC and metal grating reflector for SAW resonators.

A major benefit of SAW resonators is the large contact region with the substrate, which enables excellent heat dissipation. As shown in Fig. 7(b), the resonant frequency barely shifts (<3ppm) when input power level is increased from -7.5dBm to +10dBm. Significant $A - f$ effects have been observed in other MEMS resonators anchored using tethers [9], which introduce large thermal resistance and significant frequency shift due to self heating at high power levels. In comparison, Fig. 7(a) shows the frequency response of a tethered device fabricated on the chip at increasing power levels and the frequency shift is as high as 128ppm. A slight increase of the floor (0.03dB) is observed for the GaN SAW resonator, likely due to the nonlinear permittivity of GaN.

CONCLUSION

This paper presents a compact GaN SAW resonator design compatible with GaN MMIC technology. Applying a gradual taper to a PnC for confining the SAW, this design reduces the scattering loss of deep etched PnC reflectors by 3.5$\times$ and reduces the necessary footprint of SAW resonators by 100$\times$ compared with conventional designs using metal gratings or shallow-etched grooves. This work offers a solution for monolithic timing and RF wireless communication applications including GHz MEMS front end band pass filters with small footprint and excellent power handling in GaN MMIC technology.

ACKNOWLEDGEMENT

The authors thank Brian Schultz and Thomas Kazior at Raytheon for GaN growth and process discussions, and Prof. Steven Johnson at MIT for helpful discussion. This work was funded by DARPA DAHI Foundry N66001-13-1-4022 and NSF Career EECS-1150493.

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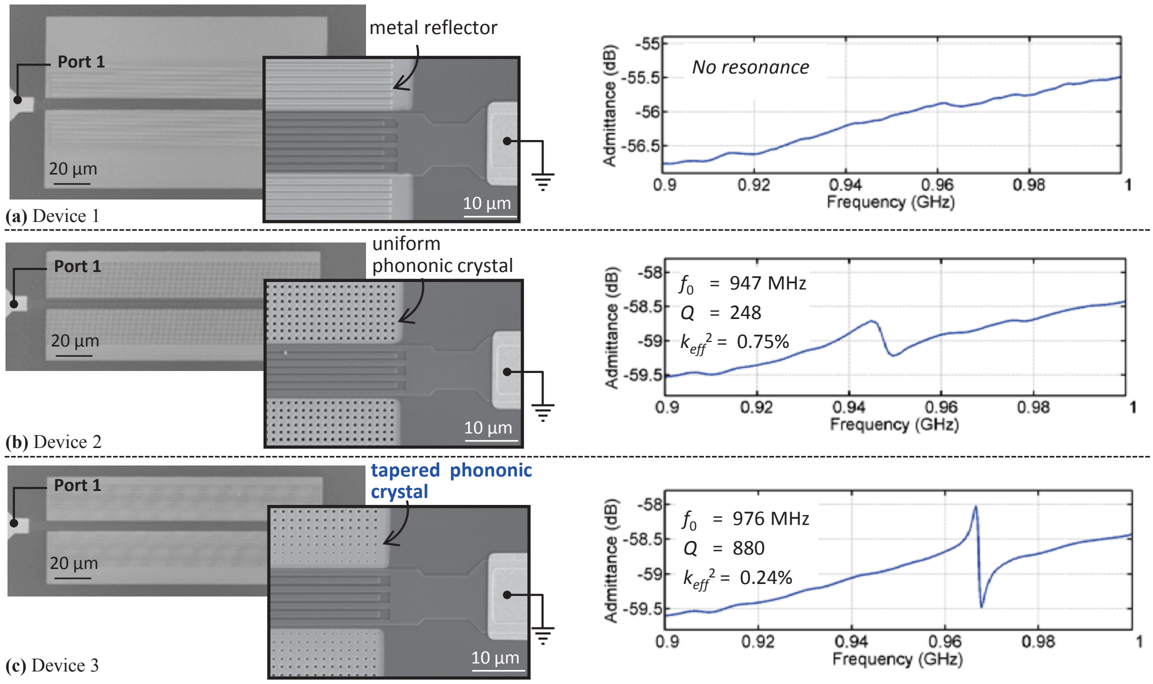

Figure 6: SEMs and measured frequency response of three types of GaN SAW resonators with identical foot print using $L' = 20$ (38.4 μm). While resonance could not be established by metal grating reflectors as shown in (a), tapered PnC resonator (c) provides 3.5× improvement in Q over uniform PnC (b).

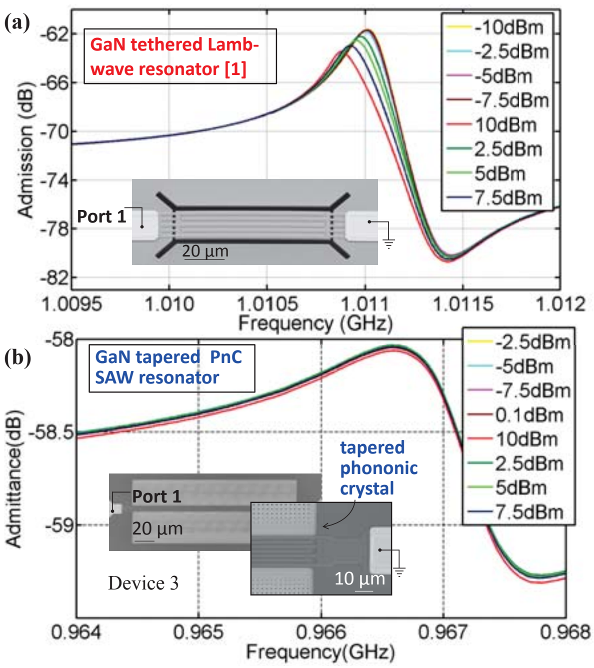

Figure 7: Admittance of the GaN tethered Lamb-wave resonator and GaN tapered PnC SAW resonator measured at various RF power levels.

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