Gallium Nitride Bulk Acoustic Wave Resonators with Embedded Metal- Silicon Dioxide Structures

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We present a novel III-nitride architecture that makes use of strong piezoelectric properties of gallium nitride (GaN) to realize high-performance micro-electro-mechanical (MEMS) resonators. Our approach is based on regrowth of GaN on a meshed metal electrode covered with a thin silicon dioxide (SiO_2). To efficiently excite bulk acoustic waves (BAWs) in the GaN layer, an electric field is applied between the embedded meshed metal electrode and a metal layer atop of the GaN film. This approach maximizes the electromechanical coupling efficiency and relies on the largest piezoelectric coefficient of GaN (d_{33}) to excite the thickness-mode resonance. The SiO_2 layer results in an improved GaN regrowth quality and also compensates for the negative temperature coefficient of elasticity (TCE) of GaN.

III-nitride piezoelectric thin films, such as GaN and aluminum nitride (AlN), are gaining increasing interest for on-chip time-keeping and sensing applications. Unlike AlN, low-temperature sputtering of GaN on metals is not yet established, restricting its growth on specific substrates. Conventionally, for exciting BAWs in GaN, a bottom electrode is sputtered as the final fabrication step after the substrate is removed from the back-side using deep reactive ion etching (DRIE) [1-3]. DRIE is costly and metal coverage on deep DRIE trenches is usually suboptimal, resulting in high resistance for the bottom metal electrode [4]. In this work, we present a new GaN resonator architecture that employs a metal layer within the piezoelectric stack and discuss its advantages from both fabrication and acoustic performance points of view. Starting with a GaN-on-Si substrate, shallow trenches are patterned in GaN and refilled with tungsten (W) and SiO_2. The sample is returned to the metal-organic chemical vapor deposition (MOCVD) reactor to regrow the thick GaN layer. The regrowth was done at National Chiao Tung University, Taiwan. The growth temperature was 1070 ºC, with a V/III ratio of 1500. Nitrogen (N_2) and hydrogen (H_2) were used as the environment gases with H_2 as the carrier gas. This technique enables front-side release of the resonant structure using xenon difluoride (XeF_2), therefore eliminating the backside DRIE step. SEM images of the refilled trenches and the cross-section of the regrown GaN are shown in Fig. 1. To prove the good quality of the regrown GaN on the meshed structure, photoluminescence (PL) measurements on the regrown GaN on the meshed structures are compared against measurement points on a reference sample (Fig. 2).

Besides facilitating the fabrication of the GaN BAW resonators through elimination of backside DRIE and metal sputtering, in the new process, we have precise control over the placement of the embedded metal electrode and can therefore excite the thickness resonance modes efficiently. Embedding the SiO_2 structures within the resonant stack can compensate for the negative TCE of the GaN layer. SiO_2, unlike most other materials has a positive TCE and is used to cancel out the effect of temperature on the elasticity and thus resonance frequency. Depositing SiO_2 on the surface of the resonator is not efficient since the surface is stress-free and larger volumes of SiO_2 will be required to fully compensate temperature-induced frequency drifts (Fig. 3). Table I compares TCF of two resonators with a total stack thickness of 3 µm with identical material and material thicknesses in the stack, one following Fig. 3 (a) configuration and one following Fig. 3 (b). It is worth noting that the TCF values reported in Fig. 3 are achieved when the SiO_2 thickness is more than 20% of the stack, while Table I suggests that an SiO_2 layer positioned within the stack, comprising only ~ 6% of the total stack thickness, can be sufficient to null the TCF (the exact thickness of the SiO_2 layer depends on the resonance mode). As seen in Table I, the resonator with embedded W/SiO_2 structure are clearly offering better performance in terms of lower TCF for the same thickness resonance modes.

References

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[4] V. Gokhale *et al.*, "Observation of the acoustoelectric effect in gallium nitride micromechanical bulk acoustic filters," *IFCS* 2010.

[5] A. Ansari *et al.*, "GaN micromechanical resonators with meshed metal bottom electrode," *Compound Semiconductor Materials,* 2014, Submitted.

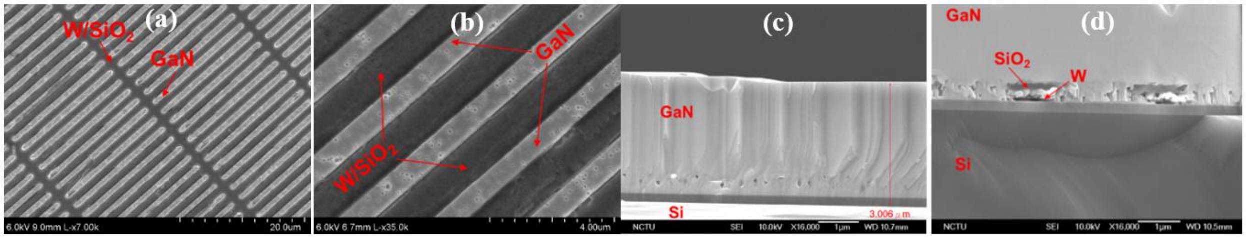


Fig. 1. SEM images of (a) 250-nm deep trenches in GaN, forming a grid-like pattern, refilled with W (100 nm)/SiO_2 (150 nm). Zoomed image is shown in (b). (c) Cross-section image of the regrown GaN on a 500 nm-thick GaN with no pattterns (reference), (d) GaN regrown on W/SiO_2 structures. GaN has well-coalesced and a uniform film is grown on top of the meshed metal electrode. GaN, W and SiO_2 layers are marked [5].

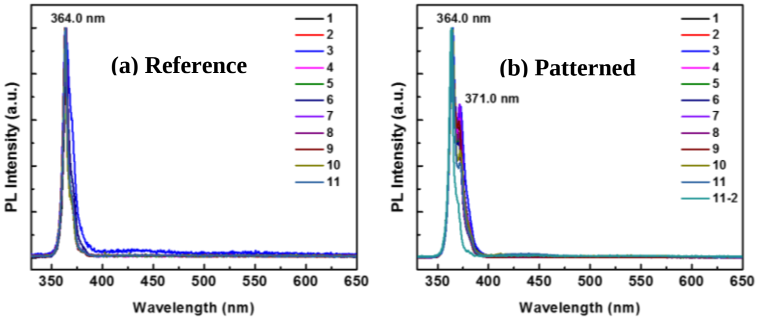


Fig. 2. Room temperature PL measurement of 11 different points on (a) the reference sample, where GaN is grown on a thin GaN buffer layer without any patterns and embedded metals (reference growth), and (b) on the W/SiO_2 patterned structures. The PL measurements clearly indicate the GaN peak (at 364 nm) is not degraded in (b) [5].

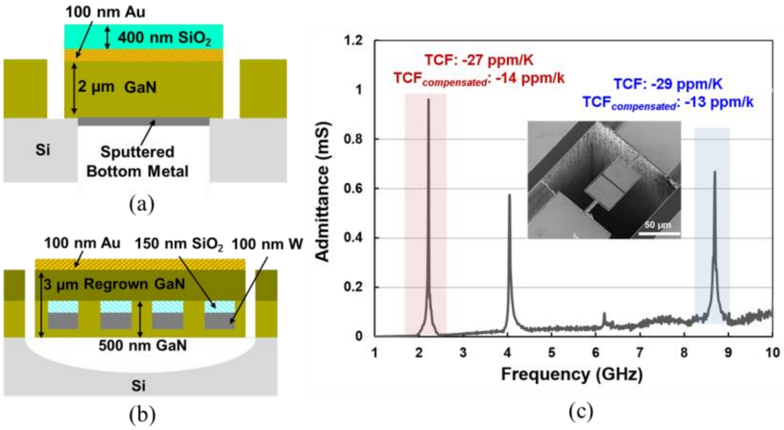


Fig. 3. (a) Schematic of a typical GaN piezoelectric resonator, released from the backside with Si DRIE. The thin oxide layer is merely used for temperature compensation of resonance frequency. (b) Schematic of the new structure presented in this work with a meshed metal electrode. The resonator is released from the front with XeF_2. (c) De-embedded measured admittance response of a thickness-mode resonator (shown in figure inset) with the stack shown in (a). The TCF of the resonator is compared before and after deposition of 400 nm SiO_2 on the top surface of the resonators [5].

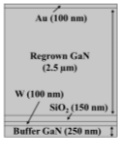
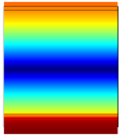
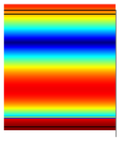
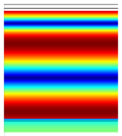
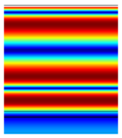
Thickness Resonance Harmonics	1st Order	2nd Order	3rd Order	4th Order
Frequency (GHz)	1.1304	2.0603	3.2092	4.5721
TCF 3 (b) (ppm/K)	-8.5	+12.2	-6.5	-15
TCF 3 (a) (ppm/K)	-25	-24.6	-23.2	-24.2
Mode Shape (b)  Au (100 nm) Regrown GaN (2.5 μm) W (100 nm) SiO$_2$ (150 nm) Buffer GaN (250 nm)				

TABLE I. Simulation results of the resonance frequency, TCF and mode shape of a resonator with a total stack thickness of 3 μm. TCF of the resonator is compared with a resonator having the same material and layer thickness, but following configuration shown in Fig. 3(a). Embedding SiO_2 layer in the structure significantly improves the TCF compensation.