Piezoresistive versus Piezoelectric Transduction of GaN Micromechanical Resonators

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Gallium nitride (GaN), in contrast to other commonly used piezoceramics, is a semiconductor that exhibits piezoresistive in addition to piezoelectric effects. The large piezoresponse – combined piezoelectric and piezoresistive effects – of GaN points out possible applications of GaN-based material systems in resonant devices. While the static piezoresistive response of GaN is small [1], the time-dependent piezoresponse of GaN electromechanical devices is much larger than that of its other semiconductor rivals, namely Si and SiC; as a result of significant piezoelectric contribution to the overall response. Hence, GaN with a large gauge factor in a heterostructure [2] has an advantage over other piezoresistive materials for time-dependent applications. Micromechanical resonators are classic examples of such time-dependent systems. In this paper, utilizing the piezoresponse of GaN, we present the design and measurement results of various types of GaN micromechanical resonators and compare the advantages and drawbacks of each method.

We use GaN grown on Si (111) to have the ability to remove the substrate easily and selectively using isotropic or anisotropic etching methods. A general schematic shown in Fig. 1 demonstrates versatile resonant devices that we implemented using GaN-on-Si substrates. The first class of devices are **bulk-mode resonators**, consisting of acoustic filters with interdigitated (IDT) electrodes, and bulk acoustic wave (BAW) resonators operated in thickness mode (Fig. 2). These types of devices exploit only the piezoelectric response of the GaN layer that is sandwiched between two electrodes. The bottom electrode can be either a metal layer that is sputtered from the backside or a silicon layer that is the device layer of a starting SOI substrate (Fig. 2 (a-d)). The latter choice offers higher *Q* and better power handling capability, while the earlier choice (GaN with thin metal electrodes) offers the highest electromechanical coupling efficiency, especially when the d_{33} piezoelectric coefficient of GaN is used. Such BAW resonators can be used for timing [3] or resonant sensing applications [4] and can be monolithically integrated with HEMTs with a few modifications to the HEMT baseline fabrication process. It should be noted that the GaN BAW filters can only be used for narrowband applications as the piezoelectric coupling coefficient (k_t^2) of GaN is relatively small. The second type of devices are **resonant HEMTs**, wherein two-dimensional electron gas (2DEG) at the AlGaN/GaN interface is used as the bottom electrode of the piezoelectric actuation, as well as the sense channel of the pickup HEMT. In such devices, several effects contribute to the resonant response of the HEMT (Fig. 3). First, the donor/conducting valley pairs shift upon resonance causing redistribution of carriers in the longitudinal and transversal energy valleys in the bulk, which is the result of the direct piezoresistive effect in GaN. As discussed earlier, the contribution of this effect is presumed to be small in n-type GaN [1]. This is due to the premise that the donor states in n-type GaN are close to the conduction band, and the donor energy levels shift together with the conduction band under the stress. Second, the vibration strain induces a vertical stress gradient across the beam, generating a polarization gradient, which in turn generates a distribution of free carriers (holes or electrons) [5] across the beam. The corresponding donors or acceptors are represented by the stress-induced change in the bonded polarization charge distribution [6]. Third, with a HEMT used to sense the bending strain, in addition to the aforementioned effects, vibration changes the stress magnitude of the already pre-stressed AlGaN barrier layer, shifting the piezo-induced 2DEG density. The resonant HEMT can be readily scaled to operate in multi GHz frequencies, with the highest reported frequency of 4.2 GHz [7] and can be monolithically integrated with HEMTs as the name suggest. The last class of devices are **metal-free resonators with 2DEG electrodes**, where the effect of metal loading on the mechanical *Q* is eliminated by patterning the AlGaN layer and using it as top electrodes. Higher mechanical *Q*s are expected with no interface loss and metal loading involved [8] but at the expense of lower electrical *Q* due to the higher electrical resistance of 2DEG electrodes. These resonators are excited through lateral electric field between two adjacent 2DEG electrodes. Unlike the two other types mentioned above, the acoustic transduction can only rely on the weaker lateral (d_{31}) piezoelectric coefficient of GaN. On the other hand, the fabrication is simpler since it does not require backside lithography and DRIE etching. The main application of metal-free resonators is in resonant sensing, where having higher mechanical *Q* outweighs the disadvantages of this device type. Depending on the application, either/all types of devices can be implemented and used [9].

References

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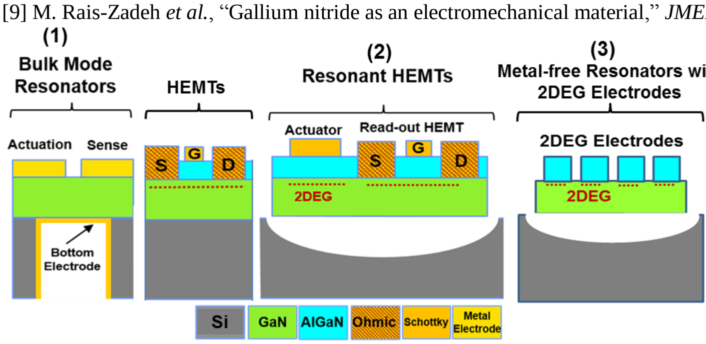

Fig. 1. A cross-section schematic demonstrating various types of GaN electromechanical devices discussed in this work. Functionally, these systems can act as clocks, sensors, acoustic filters/resonators, readout circuitry and communication nodes. These device types can potentially be co-fabricated on the same substrate, along with optoelectronic devices such as blue lasers and LEDs. This concept can be extended to GaN films grown on SOI substrates.

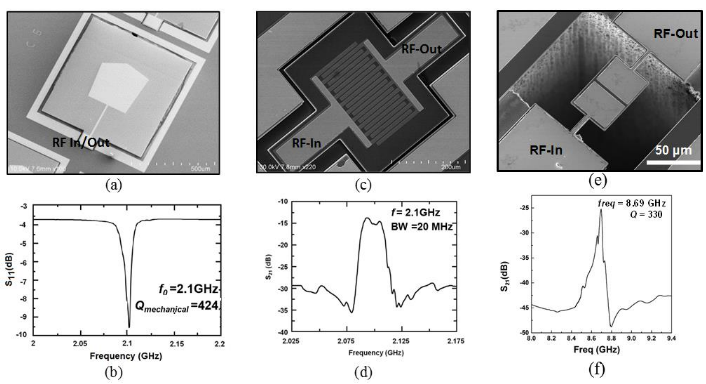

Fig. 2. Bulk mode resonators
SEM image of the fabricated GaN-based bulk acoustic devices along with the measured frequency response of the thickness-mode resonance: (a,b) GaN-on-Si film bulk acoustic resonators (FBARs), showing fundamental thickness-mode resonance at 2.1 GHz. (c,d) GaN-on-Si acoustic interdigitated transducer (IDT) filters. (e,f) Fourth-order harmonic of the thickness-mode resonance of a GaN BAW resonator at ~8.7 GHz, marking the highest resonance frequency measured on GaN BAW resonators to date.

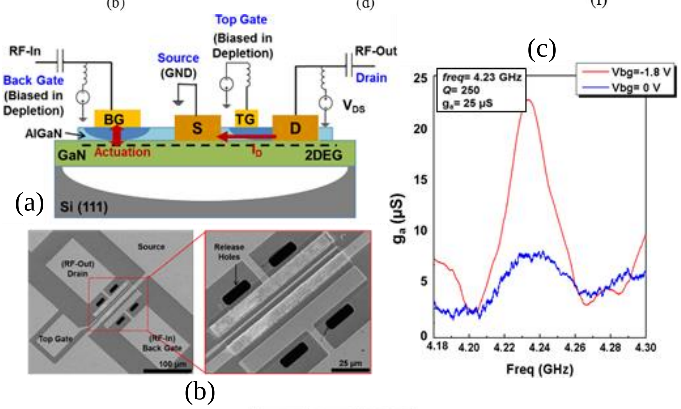

Fig. 3. Resonant HEMTs
Schematic view of an AlGaN/GaN thickness-mode resonant HEMT. AC signal is applied to the back gate or the piezoelectric actuator and picked up by sensing the drain current. (b) SEM images of the fabricated device. (c) Measured acoustic transconductance, showing the second-order thickness resonance mode at 4.2 GHz. The resonance peak is observed only when the actuator is biased in depletion.

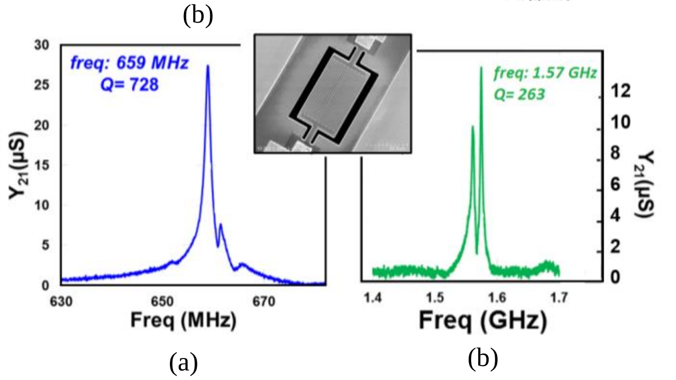

Fig. 4. Resonators with 2DEG electrodes
Measured admittance response of laterally excited metal-free GaN resonators with 2DEG top electrodes. De-embedded measured response of the 2DEG resonators at 659 MHz and 1.57 GHz are shown.