AlGaN/GaN Micromechanical Devices and Resonant HEMTs

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Piezoelectrically actuated micromechanical resonators have been a subject of extensive research for the past decade with the main goal of replacing quartz resonators in timing applications. Aluminum nitride (AlN) has been the main contender as a piezoelectric ceramic replacement for quartz since its low-temperature sputtering process has been developed. In recent years, gallium nitride (GaN) has received some attention as a material of choice for micromechanical resonators mainly due to its piezoelectric properties [1]. GaN, in contrast to other commonly used piezoceramics, is a semiconductor that exhibits piezoresistive in addition to piezoelectric effects. Although neither the static piezoresistive nor the piezoelectric response of GaN is particularly large, the combined piezoelectric and piezoresistive effects – the piezoresponse – of GaN is significant. This property of GaN can be utilized to implement micromechanical resonators with unique structures having combinatory transduction mechanisms. It has been shown that the time-dependent piezoresponse of GaN electromechanical devices is much larger than that of its other semiconductor rivals 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. Utilizing the large piezoresponse of GaN, our group has shown the highest-quality factor (Q) of >13,000, highest-frequency of > 8 GHz, as well as the highest-performance GaN micromechanical resonators with the highest measured frequency × Q values of ~ 10^{13}. In addition, making use of the stress-sensitivity of the two dimensional electron gas (2DEG) present at an AlGaN/GaN interface, we have developed resonant high electron mobility transistors (HEMTs) with unprecedented acoustic properties. For all such devices, we use GaN grown on Si (111) to have the ability to remove the substrate selectively using isotropic or anisotropic etching methods.

Fig. 1 shows a general schematic of versatile resonant devices presented in this paper. The first class of devices are passive piezoelectric resonators operated in their bulk acoustic resonant mode, consisting of a piezoelectric layer and a set of interdigitated transducer (IDT) electrodes. These types of devices exploit only the piezoelectric response of the GaN layer. Depending on whether a bottom electrode is used or not, the device makes use of the thickness mode piezoelectric coefficient (d_{33}) or is laterally driven using the d_{31} coefficient of GaN. In the former case, the bottom electrode could be either a metal electrode or a conductive Si layer that is the device layer of a starting SOI substrate (**Fig. 2 (a-f)**). Such BAW resonators can be used for timing or resonant sensing applications and can be monolithically integrated with HEMTs with a few modifications to the HEMT baseline fabrication process.

The second type of devices are resonant HEMTs, wherein the 2DEG at the AlGaN/GaN interface is used as the sense channel of the pickup HEMT. In such devices, several effects contribute to the resonant response of the HEMT (**Fig. 3**). The main effects are first, due to the vibration strain that induces a vertical stress gradient across the beam, generating a polarization gradient, which in turn generates a distribution of free carriers (holes or electrons) [3] across the beam. The corresponding donors or acceptors are represented by the stress-induced change in the bonded polarization charge distribution [4]. Second, 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 [5] and can be monolithically integrated with HEMTs as the name suggest [6].

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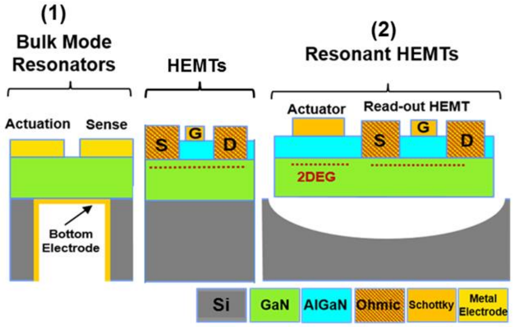

Fig. 1. A cross-section schematic demonstrating various types of GaN electromechanical devices discussed in this work. Functionally, these systems can act as clocks, sensors, acoustic filters/resonators, readout circuitry and communication nodes. These device types can potentially be co-fabricated on 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 [1].

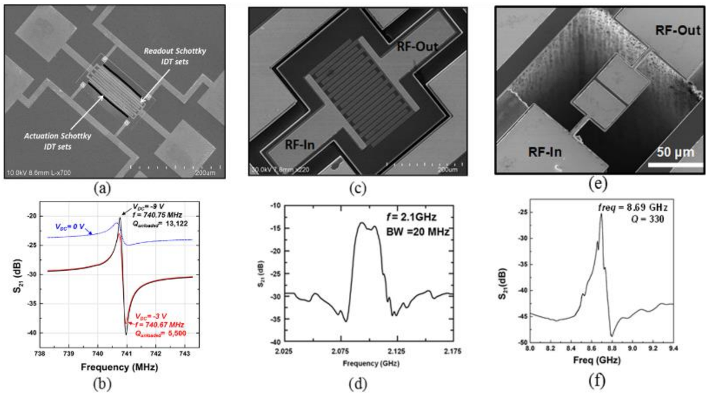

Fig. 2. SEM image of the fabricated GaN-based bulk acoustic devices along with their measured frequency response: (a,b) The highest-*Q* and *f*×*Q* GaN resonator laterally driven with IDT Schottky top electrodes. (c,d) A GaN-on-Si thickness-mode BAW filters. (e,f) 4th-order harmonic of the thickness-mode resonance of a GaN BAW resonator at ~8.7 GHz, marking the highest resonance frequency measured on GaN BAW resonators to date [7].

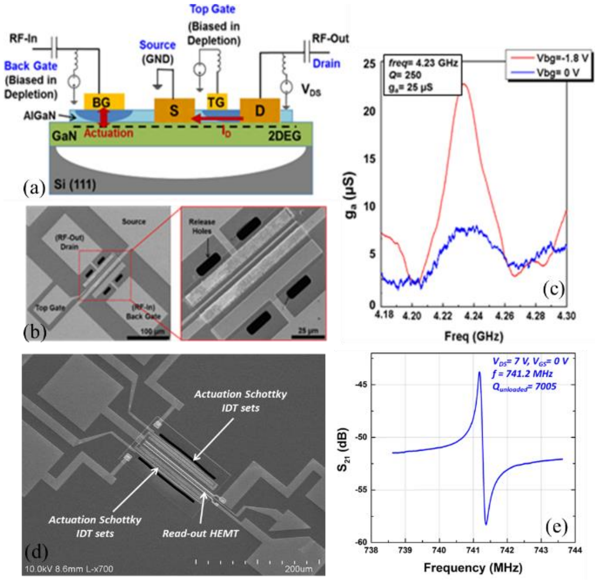

Fig. 3. (a) Schematic view of an AlGaN/GaN thickness-mode resonant HEMT. AC signal is applied to the back gate or the piezoelectric actuator and picked up by sensing the drain current. (b) SEM images of the fabricated device schematically shown in (a). (c) Measured acoustic transconductance, showing the 2nd order thickness resonance mode at 4.2 GHz. The resonance peak is observed only when the actuator is biased in depletion. (d) SEM of a resonant HEMT on a phonon trap acoustic cavity. The drive electrodes excite the Lamb mode. (e) Measured response of the laterally driven Lamb mode resonant HEMT at 741.2 MHz, showing a record high *Q* of > 7000 [8].