Lamb Wave Dispersion in Gallium Nitride Micromechanical Resonators

Haoshen Zhu, Azadeh Ansari, and Mina Rais-Zadeh
Dept. of Electrical Engineering and Computer Science, University of Michigan
Ann Arbor, MI 48105, USA
zhuha@umich.edu

***Abstract*—In this paper, we explore the phase velocity dispersion of Lamb wave in gallium nitride (GaN) thin film. For this study, ultra-high-frequency (UHF) GaN micromechanical resonators with various electrode pitch distances are designed as test vehicles. Fabricated by a process compatible with commercial monolithic microwave integrated circuit (MMIC) technology, our GaN resonators demonstrate promising performance (e.g. high quality factor of 1200 at 1GHz) and can be monolithically integrated with active (i.e. HEMTs) devices in an all-GaN platform. The zero-order symmetric (S0) and antisymmetric (A0) Lamb wave modes are observed in our measurements. The experimentally extracted phase velocity dispersion relations of GaN for both S0 and A0 modes are in good agreement with the theoretical data. Out results indicate that S0 mode is a better choice than A0 mode for high frequency GaN Lamb wave resonators because of its high phase velocity and low dispersion characteristics.**

Keywords—GaN; Micro-electro-mechanical systems (MEMS); acoustic resonator; Lamb wave; dispersion relation;

I. INTRODUCTION

III-V compounds play an important role in RF front-end modules of wireless communication systems. For instance, GaAs-based RF power amplifier (PA) and AlN-based acoustic filters (such as film bulk acoustic wave resonators (FBARs)) are now widely used in cellular devices. As more frequency bands are involved in 4G and more advanced communication systems, there is a prevailing trend to integrate both active and passive RF devices and maintain a compact form factor. An example is modular integration of GaAs PA and FBAR duplexers in current smart phones [1]. The next leap is monolithic integration of passives and actives [2]. Compared to other III-V semiconductors, GaN has superior electro-mechanical properties, useful in building high-performance acoustic devices [3]. Thus, combing GaN-based micro-electromechanical system (MEMS) with commercial MMIC technology can pave the way for fully-integrated high-performance RF frond-ends.

II. DEVICE DESIGN AND FABRICATION

The Lamb wave combines the merits of both FBAR and SAW technologies, allowing for high quality factor (Q) and multi-frequency resonators to be integrated in a single chip. GaN is a relatively new material in acoustic and MEMS domains [3] and its dispersion characteristics are not well characterized. To characterize the dispersion relation of Lamb wave in GaN, micro-resonators having interdigitated electrodes with different pitch distances are patterned on a suspended AlGaN/GaN thin film. The pitch distance defines half wavelength (λ) of Lamb wave resonance mode. Instead of grating reflectors [4], free edge reflectors are used in our design to form the acoustic cavity with a smaller footprint. As illustrated in Fig. 1 and detailed in our previous work [5], only two additional steps are required to co-fabricate the GaN Lamb wave resonators with HEMTs: (1) reactive ion etching of the GaN layer and (2) front-side release of Si substrate using xenon difluoride (XeF_2). SEM images of the fabricated devices are shown in Fig. 2. Each design is copied to 6 replicas, with different in-plane orientations (in a step of 30°) to measure the in-plane Lamb wave characteristics of GaN.

III. SIMULATIONS AND MEASUREMENTS

Fig. 3 shows simulated admittance responses of the designs with different pitch distances, assuming a fixed Q of 1000. According to the simulated dispersion curves in Fig. 4, it is easy to indentify that the two resonance peaks in Fig. 3 correspond to the A0 and S0 modes. The typical measured S0 mode frequency responses of our devices are plotted in Fig. 5. The measured motional conductance follows the simulated trend (Fig. 3), showing a significant increase with reducing the pitch distance. This is due to the improved electromechanical coupling at a increased thickness (h_{GaN}) to λ ratio. The extracted phase velocity from experiments are compared against the simulations in Fig. 4, showing good agreement. The phase velocity slightly decreases for S0 mode while increases significantly for A0 mode as the pitch distance decreases from 7 to 4μm, indicating that S0 mode is less dispersive than A0 mode. Combining high phase velocity and low dispersion as well as high electromechanical coupling, the S0 mode is more promising for high-frequency GaN resonators than the A0 mode. Moreover, for the devices with same pitch distance but different in-plane orientations, very close resonant frequencies are observed, verifying that hexagonal crystals (e.g., GaN) are in-plane isotropic.

References

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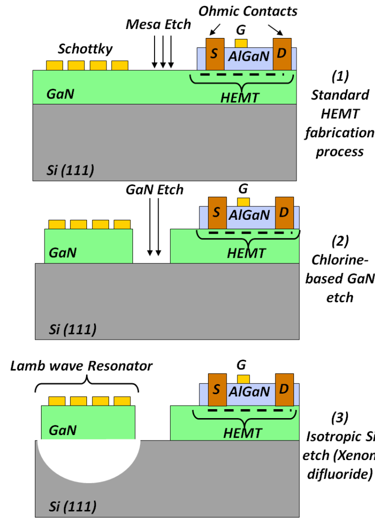

Fig. 1. Process flow for co-fabrication of GaN-based MEMS and HEMTs on a GaN-on-Silicon wafer.

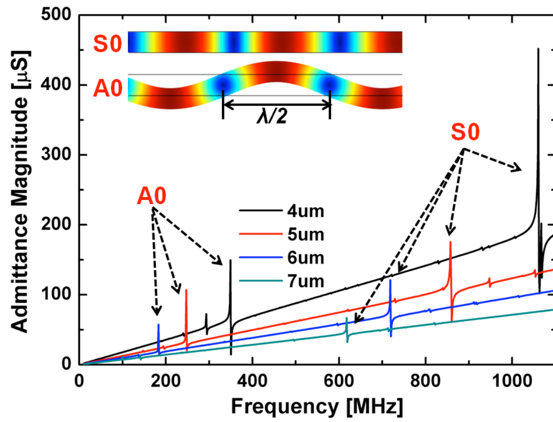

Fig. 3. The simulated admittance frequency responses for the GaN Lamb wave resonators with different pitch distances (from 4 to 7µm). The mode shapes of the distinctive S0 and A0 mode are also shown in the inset.

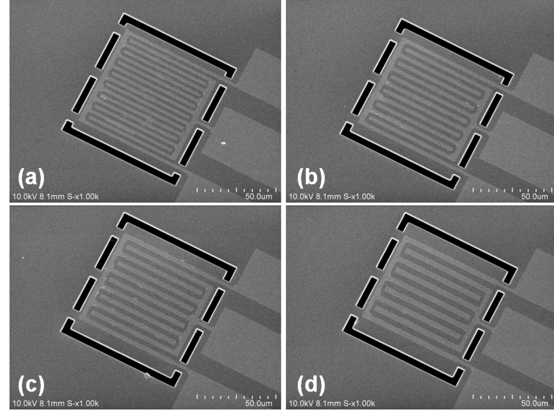

Fig. 2. SEM micrographs of the fabricated Lamb wave GaN micro-resonators with pitch distance of (a) 4µm; (b) 5µm; (c) 6µm; (d) 7µm.

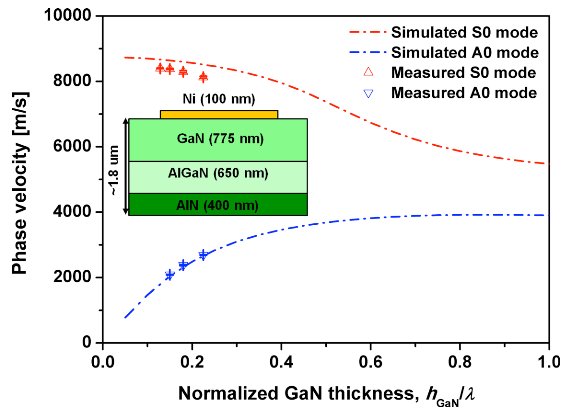

Fig. 4. Simulated and measured phase velocity dispersion of Lamb waves propagating in GaN thin film (including the AlGaN/AlN nucleation layer, as shown in the inset). The triangles and error bars are the mean value and standard deviation of the measured data over multiple devices with different in-plane orientations. The A0 mode for 7µm pitch devices was too weak to be measured (data not shown).

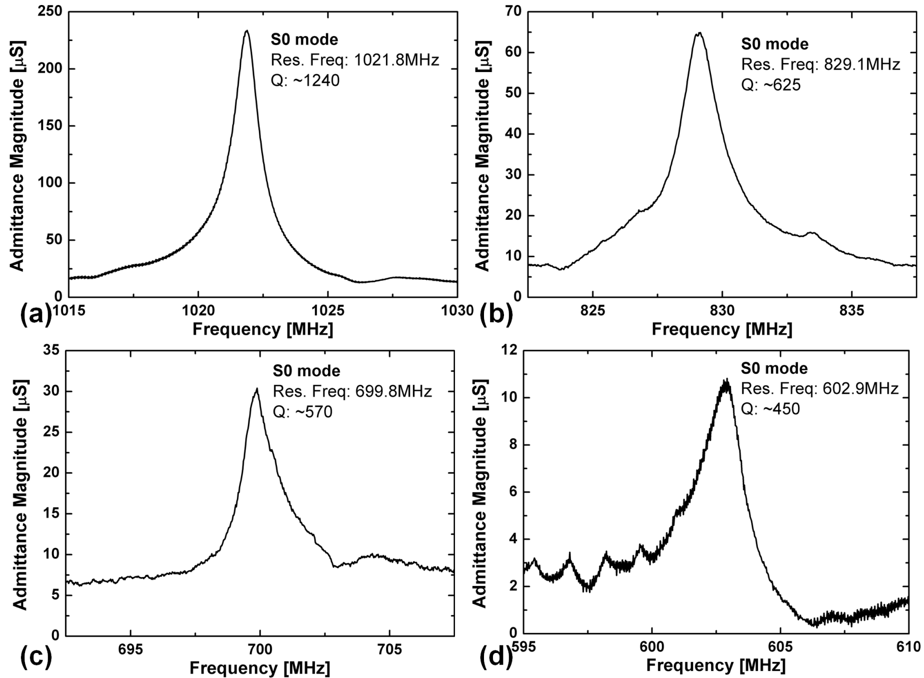

Fig. 5. Measured admittance frequency responses (de-embedded) of S0 mode Lamb wave GaN resonators with the pitch distance of (a) 4µm; (b) 5µm; (c) 6µm; (d) 7µm.