Q AMPLIFICATION IN GALLIUM NITRIDE THICKNESS MODE FILTERS USING ACOUSTOELECTRIC EFFECT

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ABSTRACT

We report, for the first time, on the observation of the acoustoelectric amplification of the quality factor in thickness-mode gallium nitride micromechanical filters. Acoustoelectric amplification, which is most effective in piezoelectric semiconductors, occurs when charge carriers drift under the influence of an applied electric field with a velocity higher than that of the acoustic wave, thus transferring energy to lower velocity phonons. We demonstrate *Q* amplification of more than 300% by applying an electric field in the direction of acoustic propagation in a 2.2 µm thick gallium nitride filter operating at 1.5 GHz. The power handling of the filter is measured by applying RF powers up to +20 dBm. No significant distortion is observed in the frequency response at elevated input powers.

INTRODUCTION

Gallium nitride (GaN) based devices have gained interest in recent years mainly because of their large band gap, high electron mobility and high power handling. There is also great potential for GaN-based resonators in sensor applications and sensing systems. In addition, high quality factor (*Q*) GaN resonators are envisioned to have far-reaching applications in frequency synthesizers and high-performance filters integrated with GaN electronics.

GaN thin-film bulk acoustic resonators (FBAR) have recently been demonstrated at gigahertz regime [1]. However, because of fabrication complexities and imperfections, the quality factor of the reported GaN resonators has not been sufficiently high for use as frequency references. In this paper, we demonstrate that the *Q* of GaN bulk acoustic filters can be electronically amplified using the acoustoelectric effect. Acoustoelectric *Q* amplification can be observed in semiconductors when an applied electric field accelerates electrons in the direction of acoustic wave propagation with a velocity higher than that of the acoustic phonons. Using the acoustoelectric effect, phonon-electron interactions may reduce (or can even cancel) the loss due to phonon-phonon interactions [2]. Therefore, *f.Q* values greater than the limit set by phonon-phonon interactions can be achieved. GaN, unlike other piezoelectric materials, possesses a high electron mobility (>900 cm^2/Vs) [3] and a high intrinsic carrier concentration, which makes it a great material for observation of the acoustoelectric effect. However, till date, due to the poor quality of GaN layers grown on silicon or non-silicon substrates and fabrication limitations in sandwiching a high quality film between metal layers, this interesting phenomenon was not experimentally verified in GaN. In this paper, we report on the first experimental verification of acoustoelectric effect in GaN bulk acoustic filters. Acoustoelectric phenomenon is manifested as an amplification of the *Q*, improvement of the insertion loss, and increase in the out-of-band rejection of filters upon application of a DC bias between the input and output RF ports, as shown schematically in Fig. 1.

Another benefit of using GaN is its superior power handling capability. GaN switches have been shown to work reliably at power levels of up to +20 dBm, and up to operating temperatures of 300 ^{o}C [4]. Similarly, GaN filters reported herein are shown to operate at power levels of up to +20 dBm without observing any distortion in the frequency response.

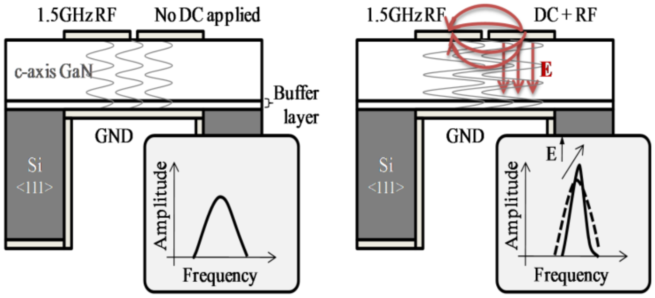

Figure 1: Cross-sectional schematic of the GaN filters showing the concept of the acoustoelectric effect and placement of the RF and DC electrodes.

ACOUSTOELECTRIC AMPLIFICATION

The theory of acoustoelectric effect was first suggested by Shaposhnikov in 1941 who discussed the absorption of acoustic wave energy by electrons [5]. Later in 1953 Parmenter substantiated this theory by observing that a DC electric current appeared in the direction of the acoustic wave propagation in piezoelectric semiconductors and concluded that this was due to the transfer of momentum between the phonon stream and the electron gas [6]. The reverse effect (i.e., the transfer of energy from electrons to the acoustic wave) was reported by Hutson in 1961 [7]. Hutson demonstrated the amplification of acoustic waves in a crystal of photoconductive CdS upon application of an external electric field. The energy transfer was analytically treated by Spector [8] for interaction of electrons and acoustic waves in the presence of a DC electric field with the material considered as a free electron gas. The two regimes under discussion included the cases where the acoustic wavelength is larger or smaller than the mean free path of the electrons. This treatment yields an analytical expression for electronic current produced solely by acoustic energy transfer. This current is in addition to the component of the current due to the DC field itself. The analytical expression for longitudinal waves yields the simple criterion that the acoustic wave will be amplified when the electron drift velocity exceeds the acoustic velocity, causing crossover from acoustic energy loss to energy gain.

One practical problem faced by investigators was the low mobility of electrons in CdS (~200 cm^2/Vs), which would necessitate the use of very high bias voltages (on the order of kilovolts) for good amplification [5]. A DC voltage in this range is not practical due to heating effects that would damage the crystalline structure. This problem was circumvented ingeniously by using the surface interactions of the piezoelectric semiconductor with a highly conductive metal, thus removing the high voltage requirements and making the DC operation regime practical [5]. This led to the development and successful implementation of *Q* amplification in surface acoustic wave (SAW) resonators.

On the other hand, there has not been much research reported on the acoustoelectric effect in bulk materials. Research on this topic has been revived recently due to the growing interest in GaN as an emerging material for use in high power and high-electron mobility transistors (HEMT) and circuits. Efforts have been made to evaluate the viability of achieving acoustoelectric amplification in bulk GaN. Significant among these recent analyses is the work by Abdelraheem et al [9] and Mensah et al [10] who analytically demonstrated that GaN is a suitable material for the observation of acoustoelectric gain.

One of the significant advantages of GaN is its high electron mobility. While theoretical models estimate mobility as high as 1500 cm^2/Vs, a maximum value of 950 cm^2/Vs has been measured [3] for GaN electron mobility at room temperature. Combined with the large piezoelectric coefficients, these values indicate that there would be strong interactions between electrons and acoustic phonons in GaN.

FABRICATION & CHARACTERIZATION

We designed and fabricated thickness mode GaN filters using GaN on <111> silicon epiwafers obtained from SOITEC [11]. Fig. 2 shows a cross section of the GaN epitaxial wafer. The wafer stack consists of 600 µm high-resistivity silicon (>10 kΩ.cm), 500 nm thick buffer layer to reduce the strain mismatch of GaN epitaxy on silicon, and 1.8 µm wurtzite GaN grown by molecular beam epitaxy (MBE). A 30 nm thick AlGaN-GaN caps the GaN layer. This layer is primarily used to generate a planar high conductivity region known as a 2D electron gas (2DEG) required for operation of HEMTs.

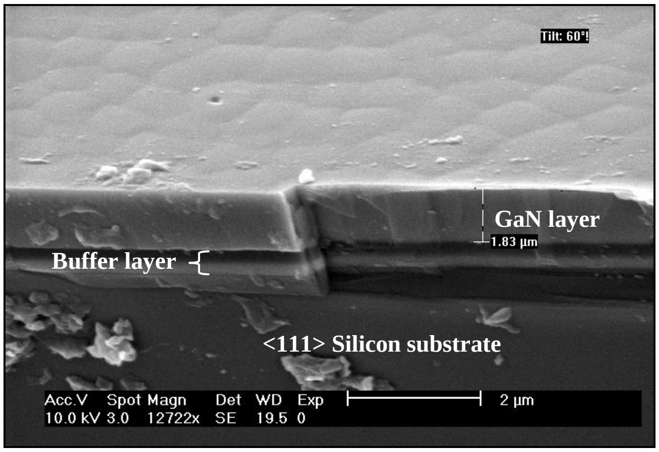

Figure 2: SEM cross section of the original wafer indicating the 1.8 µm GaN layer, the 0.5 µm buffer layer and the handle layer comprising of <111> high resistivity silicon.

The fabrication starts with deposition of a 50 nm thick PECVD silicon dioxide layer on the wafer to act as a barrier against the conductive GaN layer. Next, the GaN/silicon dioxide stack was patterned and etched down to create the individual GaN devices. The GaN etching was done in inductively coupled plasma etch (ICP) using chlorine as the primary etching chemistry. The top electrodes consisted of 10 nm Ti and 100 nm Au and were patterned using evaporation and lift-off. Devices were released by selectively removing the silicon substrate from the backside using Deep Reactive Ion Etching (DRIE). The DRIE step was deliberately designed to give a small non-vertical sidewall angle to facilitate the proper contact of the sputtered bottom electrode to the ground plane. Finally, the Ti/Au bottom electrode (10 nm/100 nm) was sputtered from the backside.

Fig. 3 (a) and Fig. 3 (b) show optical microscope and scanning electron microscope (SEM) images of two different filters with varying electrode dimensions. In Fig. 3(a), the bottom electrode is clearly seen through the transparent GaN/silicon dioxide stack.

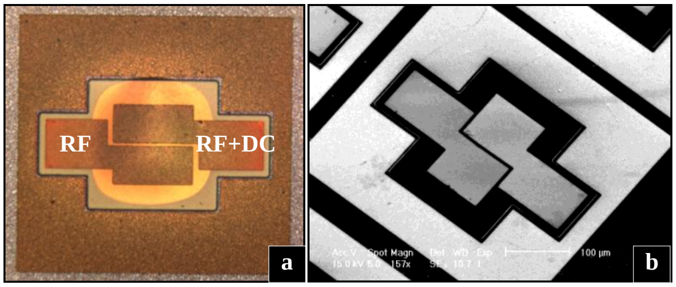

Figure 3: (a) Optical microscope and (b) SEM images of two fabricated filters. The DRIE back-etch release is seen in (a).

X-ray diffraction spectroscopy (XRD) analysis was carried out to verify the crystalline orientation and quality of the GaN film. Fig. 4 shows a clear peak resulting from the [0002] GaN centered at a detector angle (2-theta) of 34.5°. We believe that the smaller peak at 35.35° belongs to the AlN layer present in the buffer layer. The Full Width at Half Maximum (FWHM) of the [0002] GaN is measured to be 0.088°, indicating a highly oriented crystalline structure.

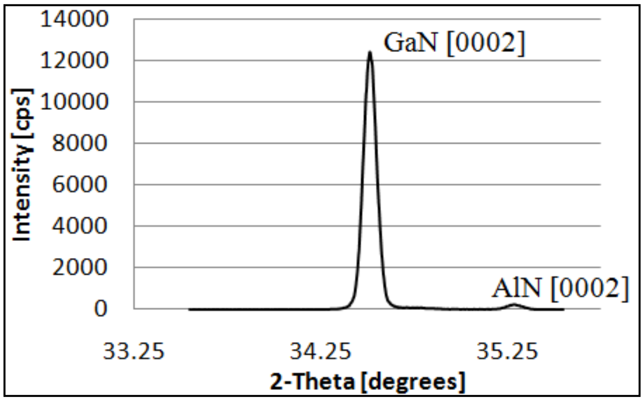

Figure 4: XRD analysis indicates that the peak for [0002] GaN is found at a detector angle of 34.51°. The FWHM for this peak is found to be 0.088° or 316.8 arc seconds.

EXPERIMENTAL DATA

The scattering parameters of the filters were measured in an air ambient using a Suss Microtek PM5 probe station and an Agilent N5241A PNA. All measurements were taken with GSG Z-probes from Cascade Microtech. Fig. 5 shows the frequency response of a thickness-mode GaN filter with effective electrode area of 90 µm × 180 µm (Device 1). The center frequency of the filter agrees with ANSYS finite element simulations (Fig. 6). The mode shape shown in Fig. 6 confirms the presence of a standing wave in the film.

The equivalent electrical model of the filter is shown in Fig. 7. We modified the Butterworth Van Dyke model to accurately simulate the performance of the fabricated GaN micromechanical filters. The center frequency and pass-band response of the filters modeled using the modified BVD configuration is in good agreement with the measured results (see Fig. 7(right)). The poor out-of-band response of the filter is due to the feed-through resistance through the conductive GaN layer. Due to fabrication limitations, the electrical connectivity to the bottom sputtered electrode is not very good. This causes a relatively large resistance from the bottom electrode to ground. By reducing the ground contact resistance using alternative fabrication processes, the performance of the filters can be significantly improved.

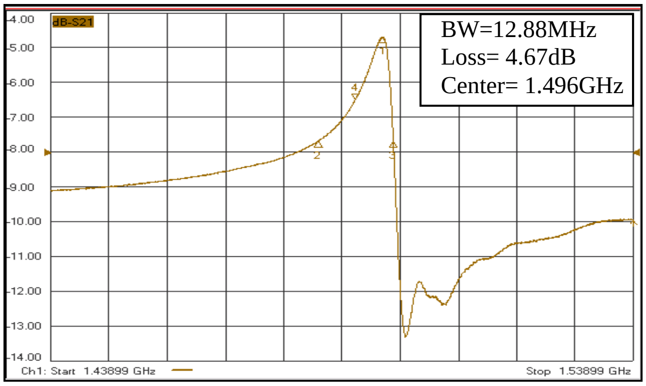

Figure 5: Measured frequency response of a 2.2 μm thick GaN micromechanical bulk mode filter.

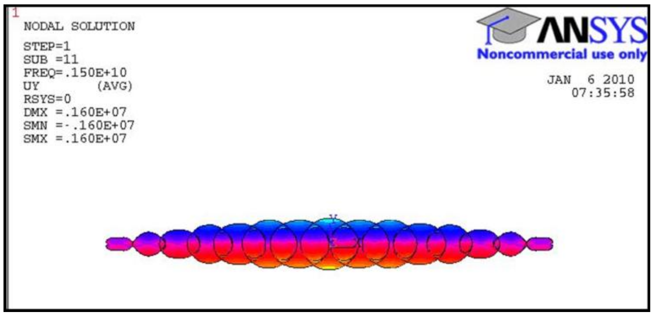

Figure 6: 2D simulation of the mode shape showing the thickness mode resonance at 1.5 GHz.

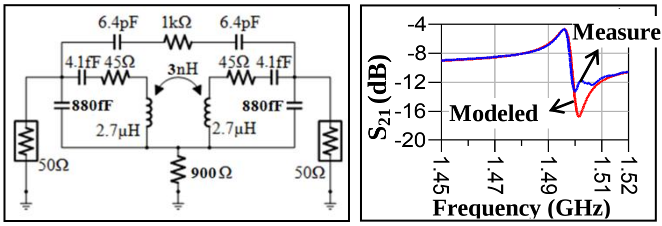

Figure 7: (left) Equivalent electrical model and (right) modeled and measured response of the filter for Device 1.

Q Amplification

The acoustoelectric effect can be used to improve the characteristics of the filters. To achieve acoustoelectric amplification in the GaN filters, DC bias was superimposed to the RF input signal using a Bias Tee from Picosecond Pulse Labs [12]. The frequency response of two filters with different electrode dimensions with increasing DC bias is shown in Figs. 8 and 9, respectively.

As shown in Fig. 8 the insertion loss of Device 1 improves up to 30 V DC, but saturates beyond this point. This trend in insertion loss could be due to the fact that the ohmic loss of the contacts and electrodes dominates the motional impedance and impedes further improvement of the loss. With an increasing electric field, the resonance frequency of the device changes slightly (by 0.057%) because of the piezoelectric effect. The maximum value of *Q* achieved for this particular device, after amplification, is 225. Similar trends in insertion loss and *Q* are observed for Device 2, as shown in Fig. 9.

The *Q* as a function of DC bias for both filters is compared in Fig. 10, indicating *Q* amplification by a value as large as 300%. For both devices, *Q* increases with the application of a DC voltage as low as 5 V (i.e., an electric field as small as 5 V/2.2 μm). There is a maximum value for the DC bias beyond which the *Q* saturates. This maximum DC value is dependent on the size of the device and the electrode geometry.

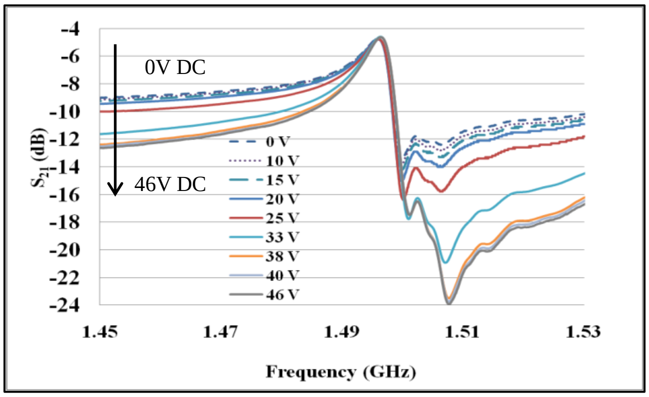

Figure 8: The acoustoelectric amplification of the filter Q for Device 1.

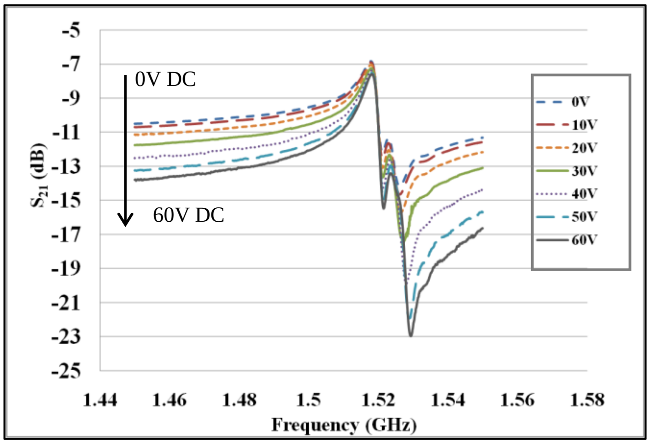

Figure 9: The acoustoelectric Q amplification for Device 2 with larger electrodes. The Q tends to saturate after 60 V DC.

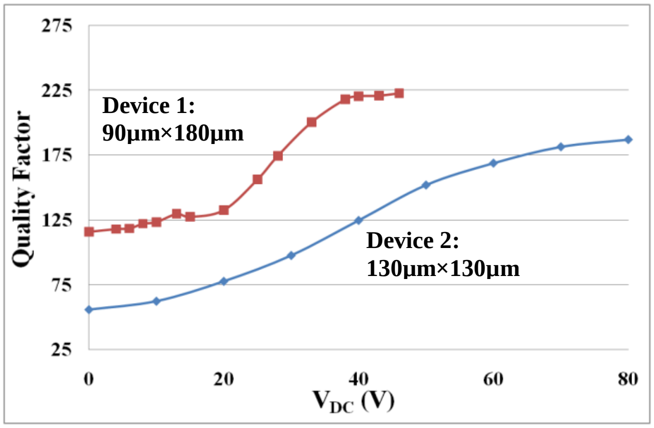

Figure 10: Trends for acoustoelectric Q amplification of Devices 1 and 2 as a function of applied DC voltage.

Repeatability

To ensure that the acoustoelectric *Q* amplification is repeatable, the response of filters is measured when DC level is switched between 0 V and 50 V over 100 times. Fig. 11 shows the *Q* of Device 2 versus switching iteration number. The *Q* value at

0V remains within 0.91% of its nominal value and the amplified *Q* remains within 0.32% of its nominal value over 100 cycles.

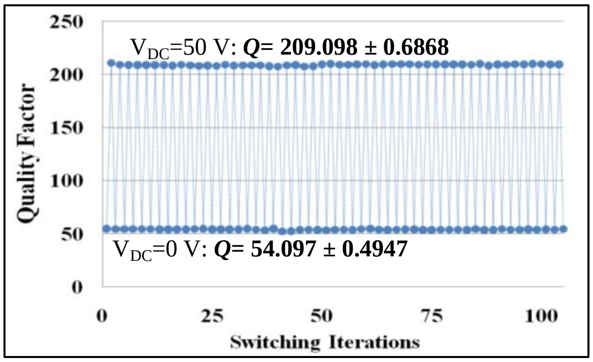

Figure 11: Measured Q at 0 V DC and 50 V DC switched over 100 cycles. The filter response switches reliably between the two values.

Power Handling

In general, micromachined piezoelectric resonators suffer from a low power handling capability due to the small form factor of the device and intrinsic material constraints and tend to show a distorted response at high power levels. The use of configurations involving piezoelectric materials on silicon improves the power handling [13]. However, thin film piezoelectric resonator and filters (such as AlN, PZT, or ZnO) have suffered from significant distortion. GaN on the other hand is known to possess good power handling capability. It has been shown that GaN MESFET switches can reliably handle up to +20 dBm of RF power without significant distortion to the response [4].

To characterize the power handling of GaN micromechanical filters, the frequency response of the fabricated filters was measured at varying power levels from -15 dBm to +20 dBm. As shown in Fig. 12, the response did not suffer any significant distortion at elevated power levels. The maximum change in center frequency and insertion loss was measured to be 0.018% and 0.7%, respectively. Fig. 12 also compares the filter characteristics at power levels of -15 dBm and +20 dBm when a DC voltage of 50 V is applied between the input and output ports. As shown, at higher DC levels the *Q* improves due to the acoustoelectric effect but the response does not get distorted with increasing RF power.

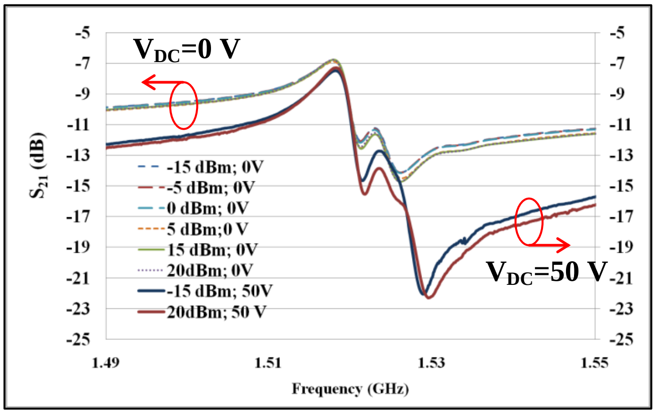

Figure 12: Response of Device 2 with RF input powers ranging from -15 dBm to +20 dBm at two different DC voltages. The pass-band response does not change or distort over the power range for either DC value.

CONCLUSION

In this paper, we reported on the observation of the acoustoelectric effect in GaN bulk acoustic filters for the first time. Using this effect, we could amplify the quality factor and improve the out-of-band rejection of the filters by applying a DC electric field in the direction of acoustic wave propagation. We believe this is a significant development in the field of acoustoelectronics since it opens up opportunities to use this effect in practical devices. The power handling of the GaN bulk acoustic filters was verified by applying RF powers as high as 20 dBm (the maximum output power of the PNA) and no distortion was observed in the frequency response. Repeatable results have been measured for a number of filters.

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