FREQUENCY-TUNABLE CURRENT-ASSISTED ALGaN/GaN ACOUSTIC RESONATORS
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ABSTRACT
This work reports on frequency tunable AlGaN/GaN acoustic resonators that utilize piezoelectric actuation based on depletion-mediated strain in the AlGaN layer and piezo-resistive readout utilizing the two-dimensional electron gas (2-DEG) induced at the AlGaN/GaN interface. The effects of the DC current flowing through (I) forward-biased Schottky inter-digitated electrodes in Class I resonators, and (II) drain/source Ohmic contacts of an integrated AlGaN/GaN HEMT in Class II resonators are studied. The readout electrodes in Class I resonators are Ni/Au Schottky contacts, whereas in Class II resonators, Ti/Al/Ti/Au metal stack is deposited and annealed to form Ohmic contacts. In both classes of devices, wide-range frequency tuning is achieved by flowing DC current through the contacts, causing large elastic modulus change due to Joule heating of the device. Frequency tuning allows for compensation of effects of fabrication variations as well as environmental changes. The 9th-order width-extensional resonance mode at 730 MHz of Class I resonators is tuned by more than 500 ppm at 25 mA of input DC power, while maintaining a quality factor (Q) of ~4,500 with no performance degradation over the tuning range. The same mode of Class II resonators at ~719 MHz shows Q amplification from 1,710 at \( V_{DS} = 4 \) V to 13,851 at \( V_{DS} = 9 \) V, with more than 2,500 ppm of frequency tuning. Resonant devices with such large frequency tuning are perfect candidates as in-situ temperature sensors, where the resonance frequency shift is an indicator of the temperature rise in the channel of the suspended HEMT.

INTRODUCTION
Piezoelectric semiconductor materials are unique test vehicles to study the interaction of acoustic waves and charge carriers in a semiconductor device. An important class of piezoelectric semiconductors is GaN, which exhibits excellent semiconducting properties as well as strong piezoelectric effects. The dependency of electromechanical properties of GaN bulk acoustic waves (BAWs) resonators on GaN doping and DC electric field has been previously studied in [1]. AlGaN/GaN hetero-structures have the added advantage of a high-conductivity two-dimensional electron gas (2-DEG) induced at their interface. Besides forming the conductive channel in high electron mobility transistors (HEMT’s), 2-DEG can be used to study the interaction between the piezoelectric strain and the 2-DEG sheet. The highly conductive 2-DEG allows for large DC current levels to flow between the contacts adding additional functionalities to the GaN-based acoustic resonators. We have previously shown AlGaN/GaN resonators with Schottky actuator and sense transducers both biased in the depletion region [2]. In order to study the effect of electric field on the mechanical properties of acoustic resonators and add frequency tunability feature to the otherwise largely non-tunable piezoelectric resonators, we introduce DC current-assisted readout scheme in two classes of devices, shown in Fig. 1. For both classes, the actuation electrodes are maintained in the depletion region, ensuring that the AlGaN layer is resistive enough to support an electric field. The effect of electric field applied to the (I) Schottky and (II) Ohmic readout contacts on the acoustic performance of devices is investigated in the following sections.

![Figure 1: Two classes of AlGaN/GaN resonators with the same acoustic cavity design and operating based on depletion of the actuation transducers. (a) Class I resonators use forward-biased Schottky contacts to readout the piezoelectric strain. (b) Class II resonators utilize an embedded HEMT to readout the strain. The readout in both cases is based on the DC current flowing between the readout contacts.](image-url)
locally modulated by application of a DC voltage and can open up a wide variety of applications for highly-tunable GaN-based acousto-electric devices [4].

**Class I resonators with forward-biased output IDTs**

Class I resonators utilize alternate depleted, forward-biased Schottky transducers to combine depletion-mediated piezoelectric actuation with current-assisted read-out scheme. Figs. 2 (a), and (b) show a scanning electron microscope (SEM) image of a Class I resonator along with the DC-IV characteristic of the output Schottky IDT set at different depletion voltages of the input IDT set. Fig. 3 shows the frequency response of the 9th-order width-extensional resonance mode at different DC voltage levels applied to the forward biased output IDT. The frequency of resonance shifts by 500 ppm, when input DC power is 25 mW. No degradation in the insertion loss or $Q$ is observed over the entire tuning range.

**Class II resonators with embedded HEMTs**

The second class of resonators utilizes a large electric field between the source and drain of the readout HEMT to sense the induced piezoelectric stress. The actuators are placed on the two sides of the device and the suspended HEMT is placed in the middle of the structure. Fig. 4(a) shows the SEM image of Class II AlGaN/GaN resonators with an integrated HEMT readout. The DC-IV curves are shown in Fig. 4(b). $S_{21}$ frequency responses at various $V_{DS}$ values are shown in Fig. 5.

**Figure 2**: (a) SEM image of the AlGaN/GaN resonator. Access to the 2DEG sheet is provided by Ohmic contacts outside of the active device area indicated as GND. (b) DC I-V curve of the forward biased output Schottky IDT, when input IDT set is biased at -10 V, -20 V, and -40 V.

**Figure 3**: Frequency response of the AlGaN/GaN resonator at its 9th-order width-extensional resonance mode at frequency of ~733 MHz and $Q$= 4,500, when the input IDT set is biased in depletion (i.e. $V_{DC}=$ -40 V) and the output IDT set is forward biased with a DC voltage varying from 2 V to 5 V. The cross section of COMSOL simulation of the stress profile in the AA' cross section shown in Fig. 2(a) is shown in the inset.

**Figure 5**: Frequency response of the AlGaN/GaN resonator at various $V_{DS}$. The quality factor of the resonator increases with an increase in the electric field applied between the source and drain. $Q$ amplification and frequency tuning is observed with application of larger DC voltages to the readout HEMT. The readout mechanism is highly sensitive to the DC voltage and Joule heating of the device. The $Q$ enhancement observed upon application of DC voltages to the readout HEMT is attributed to internal generation of thermo-elastic forces that add constructively to the initial depletion-mediated actuation force. In piezo-resistive readout schemes, the transconductance ($g_m$) is defined as:

$$g_m = \frac{i_{out}}{v_{in}} = |y_{21} - y_{12}|,$$

where $y_{21}$ and $y_{12}$ are the admittance parameters. Fig. 6 shows the piezo-resistive transconductance and its dependency on $V_{DS}$ for our Class II resonators.
**Q Enhancement Mechanism**

Significant $Q$ enhancement of $\sim 10^x$ was observed in Fig. 5, with $Q$ rising from 1,710 at $V_{DS} = 4$ V to 13,851 at $V_{DS} = 9$ V without any external feedback applied to the system. Similar $Q$ enhancement results have been reported for Si resonators with piezo-resistive [5, 6] or FET-based [7] readout, with frequencies ranging from a few MHz to several GHz.

![Piezoactuator](https://via.placeholder.com/150)

Figure 6: Frequency response of the piezo-resistive transconductance ($g_m$). $g_m$ rises to $\sim 107$ μS when $V_{DS}$ is biased at 9 V and is hardly detectable with a value of only $\sim 2$ μS at $V_{DS} = 2$ V. The inset shows the dependency of $g_m$ on $V_{DS}$.

Different mechanisms have been sought so far to explain such current-assisted $Q$ enhancement phenomenon. One possible explanation is that a series of inter-related mechanisms give rise to an alternating elastic force added in phase to the initial piezoelectric actuation force at the frequency of resonance [8]. To shed light on this phenomenon, we take a closer look at the power consumed in the readout HEMT. The dissipated power at the readout HEMT has two constitutive current components:

$$P_{DC} = R_{DS}(I_{DC} + i_{AC})^2,$$

(2)

which translate into frequency components at $f_0$ and $2f_0$ and a DC term, where $f_0$ is the frequency of resonance. At the frequency of resonance, due to the modulation of the resistance of the 2-DEG between the source and the drain ($\Delta R_{DS}$), the dissipated power varies, causing local heating/cooling of the channel. Such thermal forces give rise to elastic forces that can expand/contract the device. Depending on the phase of this additional thermo-elastic force, it can add up to or subtract from the original piezoelectric actuation force and thus at certain conditions can enhance the quality factor quite significantly [6]. Same principle is the basis of operation of parametric amplifiers and laser-driven micromechanical oscillators [9].

In our implemented HEMT-based readout scheme, the periodic drain-source resistance variation ($\Delta R_{DS}$) is utilized to sense the strain at the frequency of resonance, through a change in the drain-source voltage. Running current through $R_{DS}$ acts as an actuator itself, feeding energy from a third terminal into the system, where the additional force is dependent on $I_{DC}^2$. The generated thermal energy due to piezoresistive effect is calculated as:

$$P_{added} = \Delta R_{DS}(I_{DC})^2.$$

(3)

**Thermal Modelling**

Another advantage of using current-assisted acoustic resonators is the large frequency tuning that is only achievable through Joule heating in piezoelectric bulk-acoustic resonators. Figs. 3 and 5 show significant frequency tuning of 500 ppm and 2500 ppm upon application of 25 and 120 mW of DC power, respectively. Fig. 7 plots the frequency tuning versus the consumed power, where the linear trend proves that the Joule heating of the device is indeed responsible for the frequency tuning.

![Frequency Tuning](https://via.placeholder.com/150)

Figure 7. Frequency tuning versus consumed DC power. (a) Class 1 resonator: IDT set 1 is biased in depletion ($V_{DC} = -40$ V, -20 V, and -10 V) and IDT set 2 is biased in forward region. The slope of the linear fit is -10 ppm/mW. (b) Class 2 resonators: the slope of the linear fit is -29 ppm/mW. It must be noted that the difference in extracted slopes are attributed to different tether lengths for Classes I and II resonators caused by a larger undercut for Class I due to over-etching of the substrate.

Knowledge of the temperature of the channel of AlGaN/GaN HEMTs is essential to improve the device reliability and to optimize device design and performance; however, direct measurement of channel temperature is usually complicated. Here, we introduce a simple in-situ and non-destructive temperature sensing of the HEMT channel by using our resonant HEMTs. We then compare the extracted channel temperature using the frequency shift with the measurement results using a micro-thermocouple in contact with the surface of the HEMT channel. The temperature rise in the HEMT channel is calculated based on the consumed DC power and the thermal resistance ($R_{th}$) of the resonant HEMT by:

$$\Delta T = \Delta P_{DC} \times R_{th}.$$

(4)
The thermal resistance of the resonant HEMTs can be extracted from the slope of the frequency tuning versus DC power, plotted in Fig. 7(b), and the measured temperature coefficient of frequency (TCF) of such devices as:

\[ R_{th} = \left( \frac{\Delta f}{P_{DC}} \right) \times \frac{1}{\gamma_{CF}}, \]  

(5)

Using a slope of -29 ppm/mW from Fig. 7(b) and a measured TCF value of -27 ppm/K for such devices, the thermal resistance is calculated as \( R_{th} = 1,074 \text{K/W} \) based on Eq. 5. Plugging the extracted value of \( R_{th} \) back into Eq. 4, the temperature rise in the channel at \( P_{DC} = 110 \text{mW} \) is estimated as \( \Delta T = 118 \text{K} \).

Moreover, since the thermal resistance of the device is dominated by the thermal resistance of the two wide tethers that connect the resonator to the substrate, \( R_{th} \) can also be simply calculated as:

\[ R_{th} = \frac{1}{2} R_{tether} = \frac{1}{2} \times \frac{L}{K w t}, \]  

(6)

where \( K \) is the thermal conductivity of GaN (K = 130 W/m.K) and \( t \) is the total GaN epitaxial-layer thickness \( (t=1.8 \mu m) \). \( L \) and \( w \) are the length and width of the wide tethers. Eq. 6 yields a thermal resistance value of \( R_{th} = 1,068 \text{K/W} \), which agrees very well with the extracted \( R_{th} \) from Eq. 5.

To compare the estimated channel temperature rise using our in-situ temperature sensors with readings from a thermocouple, we utilized a micro-thermocouple that touches the surface of the suspended HEMT channel during operation. At \( P_{DC} = 110 \text{mW} \), a temperature increase of \( \Delta T = 100 + 20 \text{K} \) is measured with a thermocouple which agrees well with the \( \Delta T = 118 \text{K} \) estimated by our thermal model based on the in-situ temperature sensor. It must be noted that since the precise positioning of thermocouple tip on the channel surface was rather difficult, the temperature readings from the thermocouple are not as accurate as our resonant HEMTs and are only used to roughly estimate the temperature in the channel.

It is worth mentioning that such resonant HEMTs are ovenized in nature. That is, by flowing a constant DC current in the HEMT channel and maintaining a constant channel temperature, the device becomes essentially insensitive to normal environmental temperature changes and merely reflects the HEMT channel temperature. Such devices can be used as temperature-compensated resonators with internal \( Q \)-amplification used in frequency-stable self-sustained oscillator circuits.

CONCLUSION

In this work, we have combined depletion-mediated piezoelectric actuation with current-assisted piezo-resistive sensing. Introducing DC current in piezoelectric semiconductor devices opens up a wide variety of applications in such acoustic devices, in which the mechanical properties of propagating acoustic waves can be tailored based on the DC current flow, e.g. “acoustoelectric amplification” which relies on flow of DC current and electric field. Furthermore, application of DC current and Joule heating to the device gives rise to other actuation mechanisms such as thermal actuation, that when combined with piezo-resistive sensing, can enhance the actuation force in such devices and thus enhance the performance of the resonators. In this work, we introduced wide-range frequency tuning due to Joule heating as well as \( Q \)-enhancement with application of DC current.

The presented resonators operating at the 9th-order width-extensional mode, showing frequency \( \times Q \) values as large as \( \sim 1 \times 10^3 \) upon application of DC voltage, which is among the highest reported in the literature to date, with an added advantage of a wide frequency tuning range. The presented resonant HEMTs also act as in-situ sensors of the temperature of the HEMT channel. Furthermore, by running a fixed DC current in the HEMT channel, we can implement temperature-compensated resonators with internal \( Q \)-amplification used in self-sustained oscillators in frequency references.

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