2DEG Electrodes for Piezoelectric Transduction of AlGaN/GaN MEMS Resonators

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Abstract—A 2D electron gas (2DEG) interdigitated transducer (IDT) in Gallium Nitride (GaN) resonators is introduced and demonstrated. This metal-free transduction does not suffer from the loss mechanisms associated with more commonly used metal electrodes. As a result, this transducer can be used for both the direct interrogation of GaN electromechanical properties and the realization of high Q resonators. A 1.2 GHz bulk acoustic resonator with mechanical Q of 1885 is demonstrated, with frequency quality factor product ($f \cdot Q$) of 2.3×10^{12}, the highest measured in GaN to date.

Keywords-MEMS Resonator, IDT, Gallium Nitride, 2DEG, Compund Semiconductor, Piezoelectricity

I. INTRODUCTION

Monolithic integration of micro-electromechanical (MEM) resonators can provide basic RF and mm-wave building blocks with high Q and small footprint for use in wireless communication, microprocessor clocking, navigation and sensing applications. Direct integration of MEMS with standard integrated circuits (ICs) is motivated primarily by improved size, weight and power (SWaP), and relaxed constraints on IOs and on impedance matching [1]. Moreover, for high frequency applications (UHF band and above), this integration side-by-side with control circuits is critical for the elimination of parasitics associated with bond pads and off-chip routing.

The majority of IC integration efforts for resonators have focused on Si-based and metal-based MEMS in CMOS [2,3,4,5] where transduction mechanisms are limited to electrostatic, thermal, and piezoresistive transduction. However, many opportunities exist for MEMS in piezoelectric III-V materials used for mm-wave ICs (MMICs). Wide band-gap compound semiconductors such as GaN are used increasingly for high power (>10W/mm), high frequency (>100 GHz) applications due to high electron velocity, charge density (1×10^{13} cm^{-2} in AlGaN/GaN), and critical electric field >3 MV/cm. In its Wurtzite crystal structure, GaN also exhibits high piezoelectric coefficients (k_T^2 up to 2%) necessary for low insertion loss, large bandwidth MEMS filters.

The AlGaN/GaN heterostructure used to form High Electron Mobility Transistors (HEMTs) for MMICs is typically grown on SiC, diamond, or sapphire substrates to ensure high quality material [6]. However, the cost of such substrates has prompted the development of GaN on (111) Si. As this is a relatively new technology, material growth optimization is an active field of study. While ample information is available on the electrical properties of GaN on Si, electromechanical characterization is
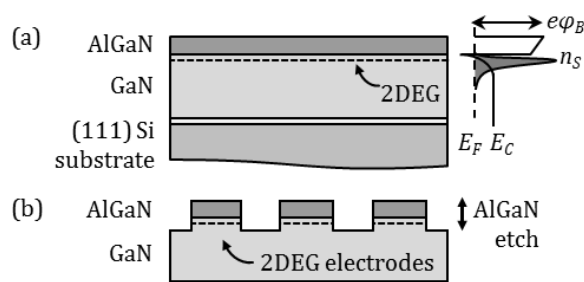

Figure 1. AlGaN/GaN heterostructure on (111) Si. (a) A 2DEG is confined in the conduction band potential well at the interface between AlGaN and GaN. (b) 2DEG electrodes are patterned via a shallow AlGaN etch.

lacking. In this work we demonstrate AlGaN/GaN resonators that can be used to intimately interrogate the electromechanical properties of GaN. These resonators are driven piezoelectrically using 2DEG interdigitated transducers (IDTs). This metal-free transduction allows for the elimination of losses associated with metal electrodes typically used in piezoelectric resonators.

II. DISSIPATION MECHANISMS IN MEMS RESONATORS

In order to isolate the intrinsic mechanical properties of GaN, it is necessary to minimize other loss mechanisms that limit the Q of a MEMS resonator. These losses can be classified into extrinsic dissipation mechanisms, which are design-dependent, and intrinsic ones, which depend on the properties and quality of the material [7]. Dominant extrinsic loss mechanisms include anchor loss and air damping. The energy dissipated into the substrate can be minimized through an appropriate anchor design. Meanwhile, air damping is less significant for high frequency bulk modes, and can be eliminated by operation at low pressure. Intrinsic mechanisms include thermoelastic damping (TED), phonon-electron scattering and phonon-phonon scattering. While TED becomes less significant in the case of high frequency bulk modes and phonon-electron interactions are not a limiting mechanism in semiconductors, phonon-phonon scattering defines the fundamental limit of resonator Q [8].

A study of this fundamental limit is required to interrogate the acoustic performance of various GaN growth processes. However, most piezoelectric transducers are realized using metal electrodes. Metal electrodes result in added acoustic losses, and contribute to mode distortion through mass loading. In AlN, efforts to minimize losses associated with metal in piezoelectric resonators have included physically separating the

electrodes from the piezoelectric film [9] and segmentation of IDT metal electrodes [10]. In GaN, the standard MMIC platform provides a metal free conductive sheet inherent to the heterostructure, which can be used to define electrodes, eliminating the metal completely from the resonant structure.

III. 2DEG ELECTRODES

The piezoelectric resonator presented here uses 2DEG IDTs to drive acoustic waves in an AlGaN/GaN heterostructure. 2DEG electrodes have previously been demonstrated as IDTs in a SAW AlGaN/GaN filter [11] as well as for piezoelectric actuation of AlGaN/GaN heterostructures [12,13]. However this is the first use of 2DEG IDTs in MEMS resonators. The authors have recently demonstrated a switchable piezoelectric transducer using the 2DEG as a bottom electrode and Schottky metal as a top electrode [14].

The starting AlGaN/GaN heterostructure used in the current work is illustrated in Fig. 1(a). Large spontaneous and piezoelectric polarizations form a sharp potential well confining electrons in a 2D plane just below the interface of AlGaN and GaN [15]. This 2DEG is conductive enough to form electrodes for piezoelectric transduction. The 2DEG can be patterned with a shallow AlGaN etch as shown in Fig. 1(b). To drive acoustic waves in the structure, an AC electric field is applied through the GaN, between the interdigitated 2DEG electrodes.

At resonance, strain fields defined by the mode shape induce a polarization field through the direct piezoelectric effect. For Wurtzite crystal materials such as GaN, the induced polarization field can be written as:

$$P_{PE} = (e_{51}\epsilon_{zx})\hat{x} + (e_{51}\epsilon_{yz})\hat{y}$$
$$+ (e_{31}\epsilon_x + e_{31}\epsilon_y + e_{33}\epsilon_z)\hat{z} \qquad (1)$$

Taking z along the Wurtzite c-axis, ϵ_x, ϵ_y, and ϵ_z are the strains along the x, y and z-axis, respectively, and ϵ_{yz} and ϵ_{zx} are shear strains. Here, e_{31}, e_{33} and e_{51} are the piezoelectric coefficients found in the Wurtzite crystal structure. There are two contributions to the bound charges associated with this polarization field. First, an interface charge σ is generated by a discontinuity in the polarization at the AlGaN/GaN interface:

$$\sigma = (P_{PE,AlGaN} - P_{PE,GaN}) \cdot \hat{z} \qquad (2)$$

Second, the polarization generates volume charge ρ throughout the heterostructure:

$$\rho = -\nabla \cdot P_{PE} \qquad (3)$$

The overall mechanically induced charge is found by integrating σ along the AlGaN/GaN interface in the region defined by the IDT and integrating ρ over the GaN volume under the IDT. The summed contribution of the interface and bulk charges is compensated by free charge flowing into the 2DEG, which translates into an AC current.

IV. FABRICATION

The ability to form metal-free electrodes is dependent on the presence of a 2DEG, which is an inherent feature of existing GaN MMIC technology. This
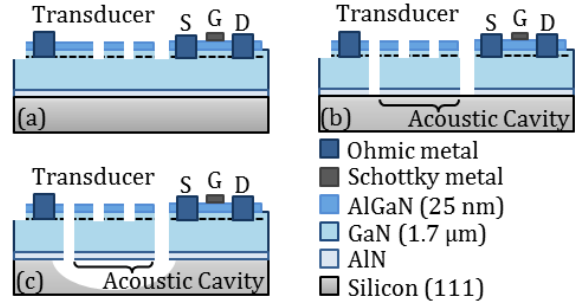

Figure 2. Fabrication involves two additional steps to (a) existing GaN MMIC technology, including (b) a deep GaN etch, and (c) a release step.

platform can be leveraged to fabricate 2DEG IDT piezoelectric resonators with only two additional masks as shown in Fig. 2. The starting material is an AlGaN(25nm)/GaN(1.7μm) stack grown by Molecular Beam Epitaxy on a (111) Silicon substrate, using a thin AlN nucleation layer [16]. The growth of the material in this work was performed at Raytheon with subsequent fabrication at MIT. A shallow BCl_3/Cl_2 plasma etch of the AlGaN is used for both electrical isolation between devices and patterning the 2DEG IDTs. The 2DEG is removed from the regions where the AlGaN is etched away, by eliminating the potential well generated by the AlGaN/GaN interface.

A Ti/Al/Ni/Au metal stack is deposited and patterned, followed by a rapid thermal anneal (RTA at 870˚C, 30 sec) to form Ohmic contacts to the 2DEG. While in a typical HEMT process flow these Ohmics are used to access the source and drain of the transistors, in this work they also serve as a means of electrically contacting the 2DEG electrodes. This takes place outside of the resonant cavity to avoid metal loading. From the Ohmic metal contact, the 2DEG forms a conductive path through the suspension beams onto the resonator. At this point, the piezoelectric transducer is completely defined. To extend the process for the inclusion of HEMTs, a Ni/Au/Ni gate metal stack can be deposited and patterned to form Schottky contacts for the gate (Fig. 2(a)). An additional Cl_2 inductively coupled plasma etch of the GaN layer defines the acoustic cavity (Fig. 2(b)). Finally, a XeF_2 isotropic Si etch releases the resonators from the substrate (Fig. 2(c)).

V. RESULTS

A GaN piezoelectric resonator using a 2DEG IDT is shown in Fig. 3(a), with the simulated resonant mode shape shown in Fig. 3(b). This structure corresponds to "Design A", with dimensions 50 by 65 μm and using quarter wavelength suspension beams to minimize anchor losses. For comparison, an identical resonator using Ohmic metal IDTs is also fabricated.

Devices were tested under vacuum to reduce air damping. A 50Ω terminated 2-port measurement was performed. The parasitics of the RF pads were deembedded using an open structure. Since the goal of this work is to isolate the mechanical performance of the AlGaN/GaN resonators, further deembedding needs to be
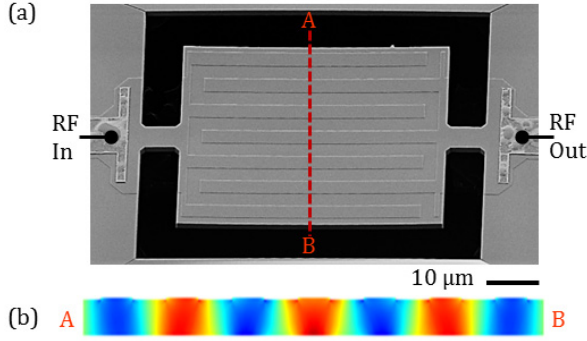
(a)

(b) A   B

Figure 3. (a) SEM of GaN resonator with 2DEG IDT. The 2DEG electrodes are patterned with a 70 nm deep AlGaN etch. Ohmic contacts are used to access the 2DEG outside of the resonant structure. (b) Strain fields of the bulk contour mode excited using the 2DEG IDT.
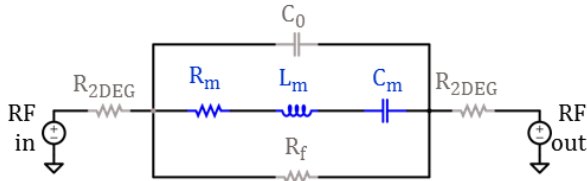

Figure 4. Equivalent circuit model of 2DEG IDT. Elements in blue represent the mechanical resonance while elements in grey are electrical parasitics of the structure and are deembedded from the measurement.

performed to eliminate electrical parasitics, especially the loss associated with feed-through capacitance and the series resistance of the 2DEG. The equivalent circuit describing this device is captured by Fig. 4. After parameter fitting was performed to extract C_0, R_f, and R_{2DEG}, these contributions were deembedded from the admittance of the device, leaving only the mechanical response shown in Fig. 5(a). The measured deembedded frequency response of the resonator with Ohmic metal IDT is shown in Fig. 5(b). The mechanical quality factor of the device with metal electrodes is 3× lower than that of the 2DEG IDT, which can be attributed to the additional damping mechanisms associated with metal electrodes, as discussed in §II.

Table 1 summarizes the extracted mechanical Q and $f \cdot Q$ products for two resonator designs, each measured using 2DEG IDTs and metal IDTs. As mentioned above, "Design A" resonators use quarter wavelength suspension beams. In the case of "Design B", a phononic crystal is used to mechanically isolate the resonant mode. In both cases, the Q of the 2DEG IDT device is significantly higher than that of the metal IDT.

TABLE I.   COMPARISON OF 2DEG AND METAL IDT RESONATORS

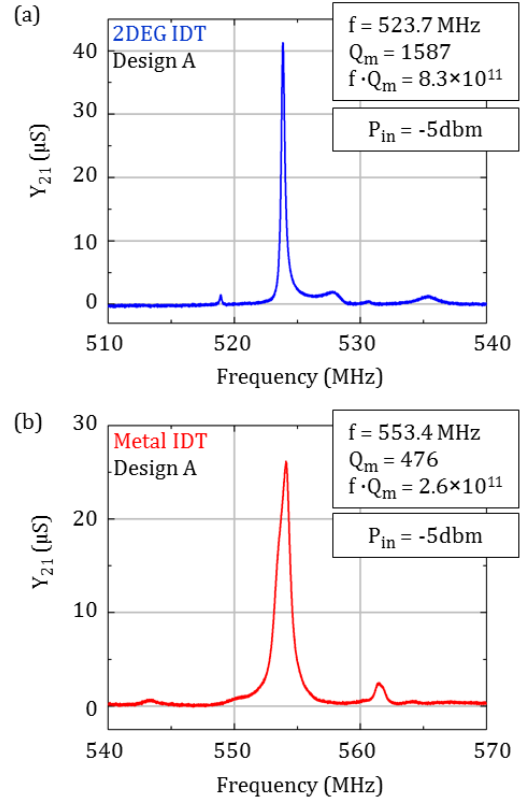|		Extracted Parameters			
		f (MHz)	Q_m	$f \cdot Q_m$ (s^{-1})	k_T^2 (%)
Design A	2DEG	523.7	1587	8.3×10^{11}	0.091
	Metal	553.4	476	2.6×10^{11}	0.095
Design B	2DEG	525.3	1193	6.3×10^{11}	0.08
	Metal	516.4	460	2.3×10^{11}	0.05

(a)

(b)

Figure 5. (a) Frequency response of "Design A" resonator using 2DEG IDT after deembedding the electrical parasitics. (b) The deembedded measured response of a metal IDT resonator with equivalent design.
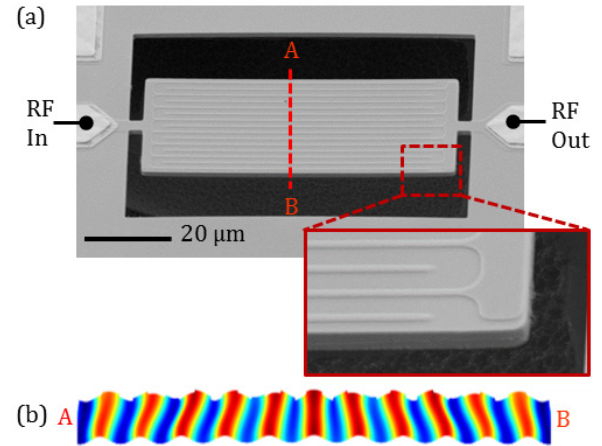
(a)

(b) A   B

Figure 6. (a) SEM of 1.2 GHz 2DEG IDT resonator. The 2DEG electrodes are patterned with a 90 nm deep AlGaN etch. (b) Mode shape showing the strain fields induced at resonance.

A 2DEG IDT designed to operate at 1.2 GHz is shown in Fig. 6(a), with the simulated mode shape illustrated in Fig. 6(b). This device was tested under vacuum, and the same deembedding technique described above was used to extract the mechanical frequency response. A bulk mode resonance was detected at 1.22 GHz with a Q of 1885, which is the highest measured $f \cdot Q$ product in GaN to date.
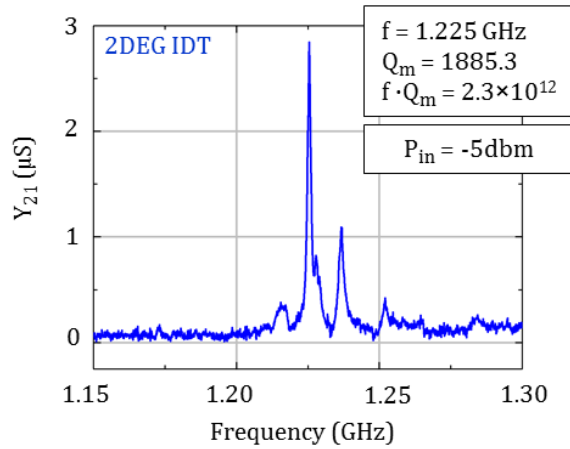
Figure 7. Deembedded frequency response of 1.22 GHz 2DEG IDT resonator. The extracted mechanical resonance has the highest $f{\cdot}Q$ product measured in GaN to date ($2.3{\times}10^{12}$ at 1.225 GHz).

Figure 8. The 2DEG IDT resonator demonstrated here achieved the highest $f{\cdot}Q$ product in GaN resonators. Ref. 19 shows $f{\cdot}Q$ of $6.9{\times}10^{12}$ in a Si-loaded resonator, which does not represent intrinsic GaN properties.

VI. CONCLUSION

We have introduced and demonstrated a GaN piezoelectric resonator that uses 2DEG electrodes to drive and sense acoustic waves. This resonator is metal-free, enabling the highest mechanical $f{\cdot}Q$ product in GaN to date at $2.3{\times}10^{12}$. A benchmarking of this work against state-of-the-art GaN resonators is shown in Fig. 8. Ref. [19] demonstrates an $f{\cdot}Q$ of $6.9{\times}10^{12}$ at 6.3 GHz, represented by the black data point. It should be noted that this device uses silicon loading to boost Q, so it is not representative of the fundamental limits of GaN.

This demonstration of metal-free resonators allows for the intimate interrogation of GaN material properties, in the absence of losses and distortions associated with metal electrodes. This work was realized in a standard MMIC heterostructure, with only two modifications to the HEMT process flow. This highlights the potential of 2DEG electrodes for benchmarking the electro-mechanical properties of GaN for material optimization.

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[4] J. L. Lopez, J. Verd, J. Teva, G. Murillo, J. Giner, F. Torres, A. Uranga, G. Abadal, and N. Barniol, "Integration o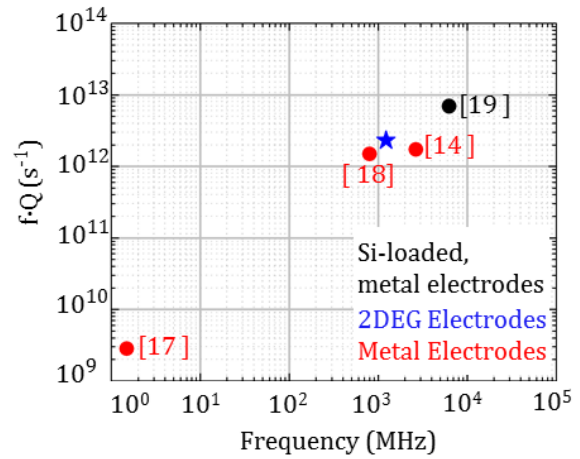f RF-MEMS resonators on submicrometric commercial CMOS technologies," *J.Micromech. Microeng.*, vol. 19(1), 13-22 (2009).

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