Monolithic integration of surface acoustic wave (SAW) filters on GaN HEMT dies: *Avoiding impedance matching through energy trapping*

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Keywords: SAW filters, RF front-end, 5G, integration, GaN, piezoelectric, acoustic wave, impedance matching

Abstract:

We explore the design and fabrication of surface acoustic wave (SAW) filters on gallium nitride (GaN) transistor dies to achieve monolithic integration of high-frequency RF filters for 5G applications. The GaN platform provides some unique advantages, one of which is the ability to design transducers that exploit acoustic energy trapping. These devices, which work with higher order Rayleigh modes, can be designed to have an impedance ~ 50Ω. This avoids the need for external impedance matching networks greatly simplifying the design and layout of integrated high-frequency RF filters.

INTRODUCTION

A modern smartphone requires on the order of radio frequency (RF) filters to enable communications using different frequency bands (for ex: cellular, WiFi, Bluetooth, GPS) [1,2]. Currently, the RF filtering is done using multiple discrete filters put together in a packaging tour-de-force (for ex: Qualcomm's RF 360 and Qorvo Fusion). While this might work in the near term, as 5G kicks in and the filtering requirements become more cumbersome (more communication bands operating at higher frequencies), an integrated solution to the problem is desired. While there has been a lot of work done on integrating Aluminum Nitride (AlN) filters in a CMOS platform [3], building suspended film bulk acoustic wave resonator (FBAR) filters on top of CMOS dies has proved challenging, mainly because of process constraints between MEMS and CMOS foundries [4].

In this work, we instead explore a GaN high-electron mobility transistor (HEMT) platform for monolithic filter integration. This work aims builds on two recent trends: *improvements in GaN epitaxial growth*, especially with thin buffer layers for RF and the *availability of GaN foundries* providing access to pre-fabricated high performance HEMT designs allowing the filters to be introduced in a post-processing step. From a materials perspective, the GaN platform provides some key advantages over the AlN-Si platform [5]. GaN HEMTs have significantly higher electron mobilities than silicon [6] which is key for high frequency operation. In addition, the higher bandgap supports higher breakdown voltages making GaN the material of choice for high power amplifiers. GaN amplifiers have steadily replaced GaAs amplifiers in both base-stations and handsets and the trend is expected to continue in the near future. While AlN has a higher bulk piezoelectric coefficient than GaN, achieving that in a deposited thin film has proved challenging. In addition, working with a polycrystalline material places limits on the ultimate mechanical quality factor achievable [7]. GaN, on the other hand, provides a *single-crystal medium* for guiding acoustic waves, hence the usually stated figure of merit for filters ($k^2{}_{eff} * Q_m$), where $k^2{}_{eff}$ is the effective coupling coefficient for the device and Q_m is the mechanical quality factor, is expected to be comparable for both platforms as we can in principle trade-off the lower $k^2{}_{eff}$ with higher Q_m depending on the application [8]. Finally, and most importantly for this work, *GaN has a lower acoustic velocity than the substrate material (usually silicon or silicon carbide)* and this allows acoustic waveguiding and significant energy trapping in the devices. This allows us to build interdigitated transducer based acoustic resonators that are effectively matched to 50-ohm input impedances. This allows one to minimize RF reflection and achieve almost perfect conversion of RF energy to the acoustic domain without the need for external impedance matching circuits. Avoiding external impedance matching is key to integration and packaging as it removes the need for off-chip inductors for each filter.

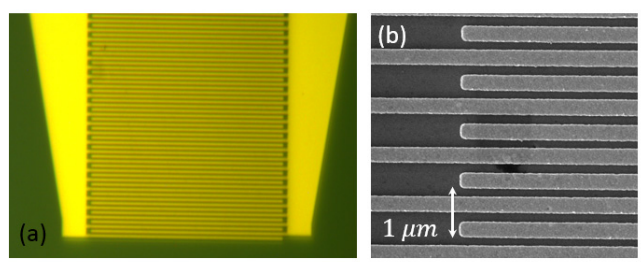

Fig. 1. (a) Optical micrograph of a fabricated IDT device. (b) Scanning electron microscope (SEM) image of a 1 μm period IDT.

ENERGY TRAPPING OF GUIDED WAVE MODES

Surface acoustic wave (SAW) filters have a long history of being used in RF communication [9]. They form the dominant RF filtering technology at low frequencies (< 2 GHz) and are commonly fabricated in strongly piezoelectric materials like Lithium Tantalate. SAW filters consist of interdigitated transducers (IDT) to convert energy back and

forth between the RF and acoustic domains. The IDT is made up of a series of metallic electrodes whose period is chosen to match the acoustic wavelength in a piezoelectric material. At the appropriate RF frequency, an acoustic wave is efficiently excited at the input IDT, propagates across the surface and is detected at the output IDT. Since the IDTs are frequency selective, the RF signal is transmitted from input to output only for the frequencies that fall within the IDT transmission band. The main advantage of SAW filters over other acoustic wave filtering technologies (like FBAR and BAW) is the ease with which the frequency of the filter can be defined by modifying the period of the interdigitated transducer (IDT), shown in Fig. 1(a). In contrast, FBAR and BAW rely on a film thickness dependent resonance to achieve filtering [1]. Traditionally, FBARs have provided higher Q_m and coupling ($k^2{}_{eff}$) at higher frequencies (> 2.5 GHz) at the expense of a more complicated fabrication process, usually involving film suspension. *Lamb wave resonators* (also referred to as contour mode resonators in the literature) try and combine the best of both worlds by merging the high Q of FBARs with the frequency tunability of SAW but these filters still require that the substrate be removed to allow the acoustic energy to be confined effectively [10]. While this is necessary in AlN on account of its high acoustic velocity which prevents guided modes from existing on an unreleased substrate, using a slow mechanical material like GaN provides the promise of realizing a CMR-like device with high Q without the need for substrate release.

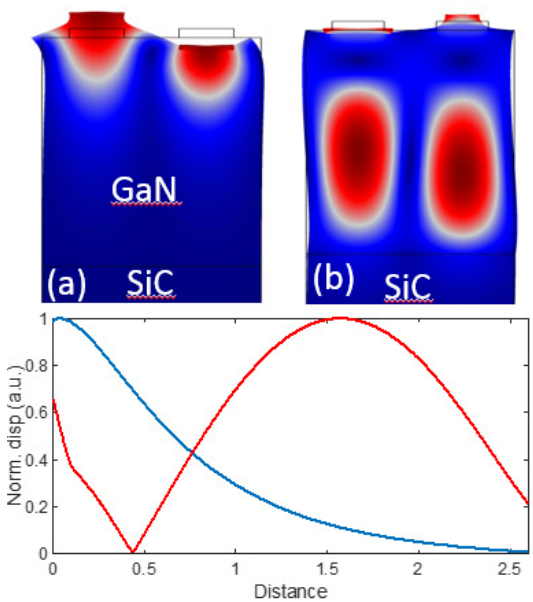

Fig. 2. Finite element simulation showing the total displacement of (a) Fundamental Rayleigh mode (b) Higher order mode (c) displacement as a function of depth.

In addition to the fundamental Rayleigh mode (Figure 2(a)), higher order modes (Figure 2(b)) exist on multilayer substrates depending on the substrate thickness. GaN is conventionally grown on a non-lattice matched substrate like Si [111] and SiC, which also turn out to be acoustically mismatched. In particular, the longitudinal acoustic velocity of GaN is less than that of both Si and SiC, which allows one to excite acoustic guided modes in a GaN on Si multilayer. Here, the slow acoustic velocity of GaN ($v_{L,Bulk}$ = 7960 m/s) is less than Si [111] ($v_{L,Bulk}$ = 9360 m/s) and SiC [111] ($v_{L,Bulk}$ = 10,100 m/s). This is in contrast with AlN which has a higher acoustic wave velocity ($v_{L,Bulk}$ = 11,200 m/s) than both Si and SiC forbidding the existence of guided modes and reducing the mechanical quality factor by energy leakage into the substrate. This has necessitated the use of membranes / substrate removal for the formation of high-Q FBAR filters [5], which brings additional fabrication complications.

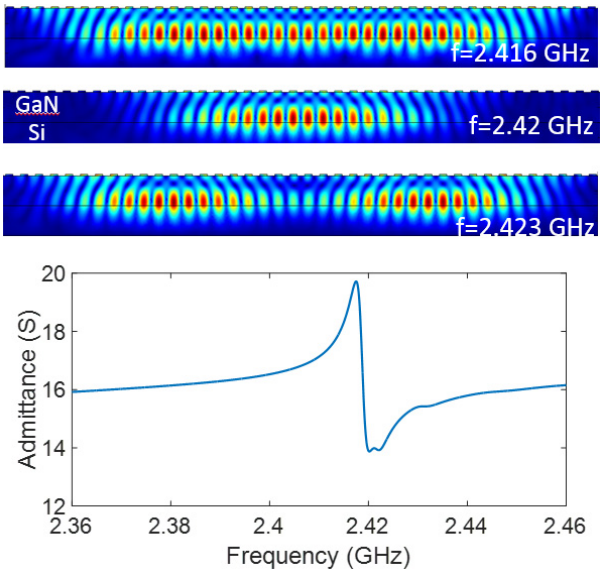

Fig. 3. Finite element simulation showing the total displacement of a GaN on Si device as the RF excitation frequency is swept. We can clearly see the energy trapping and localisation at f = 2.42 GHz (IDT period = 2 µm)

To excite the higher order waveguide modes in GaN, we start with a GaN HEMT substrate and etch the GaN device layers so that the final thickness of the GaN stack (t_{GaN}) is comparable to the acoustic wavelength (λ_{GaN}). This condition guarantees strong reflection at the metallic electrodes (Cr/Au) and thus energy trapping inside the IDT structure [11]. The trapped acoustic energy modifies the effective impedance of the device and allows us to couple almost 90% of the incident RF energy into acoustic energy, avoiding the need for impedance matching (Figure 1c). One way to understand the impedance matching is to think of the electrical equivalent circuit of the SAW device transforming from a transducer (Figure 4a) to that of a resonator (Figure 4b), represented by a Butterworth-van Dyke equivalent circuit. The higher order mode also has a much higher effective quality factor as can be seen by comparing the sharpness of the dips in Figure 4a and 4b. The higher quality factor originates from the decreased overlap of the displacement function of the higher

order mode with the metallic electrode (Figure 2c). The higher order mode has a displacement peak in the bulk, about 1 μm from the metallic electrodes whereas the fundamental mode is peaked right at the surface. The metallic electrode reduces the quality factor by acoustic dissipation and scattering, both of which become worse as we move to higher frequencies.

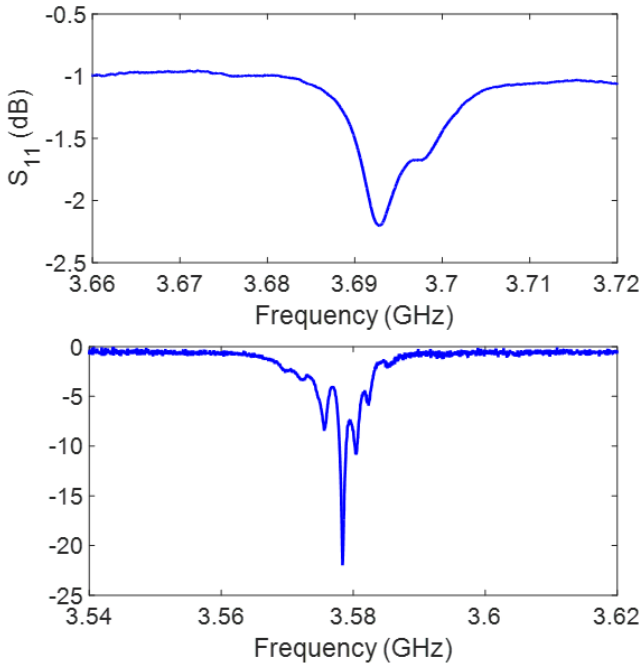

Fig. 4. RF reflection measurement (S_{11}) of an IDT structure on GaN with no energy trapping (GaN layer thickness approximately 4 μm). (b) Same device geometry as (a), except with energy trapping (GaN layer thickness approx. 1.6 μm). In case (b), roughly 90% of the RF energy is coupled into the cavity at resonance.

To visualize the acoustic energy trapping, Figure 3 shows a plot of the IDT displacement as the applied RF frequency swept from 2.3 to 2.5 GHz. The GaN film thickness is 2 μm and the IDT period is chosen equal to the film thickness. When the IDT frequency is swept, we can see that at the resonant frequency (f = 2.42 GHz), the acoustic energy is localized inside the structure [11]. The energy trapping significantly modifies the transfer characteristics of the IDT. In this cavity regime, an S_{11} dip approaching zero signifies critical coupling, where the coupling rate from the RF input into the cavity matches the cavity loss rate. As the frequency is detuned from the central resonance frequency, other resonant modes (locally trapped) are found in the structure. One can understand the origin of these trapped modes by formulating a scattering matrix of a single IDT unit cell (following 11) and concatenating the S-matrices to obtain the system response. As the frequency is changed, the effective phase picked up in transmission, reflection and propagation slightly changes leading to constructive interference (which leads to energy trapping) in different domains. We would like to note here that in the simulations, all the IDTs are excited in phase whereas in the experiment, there is a small phase difference due to the end-on excitation from the RF probe. The S_{11}spectrum in Fig. 4(b) shows the multiple discrete resonances that occur inside this system. As a rough indicator, if the localization length of a trapped mode is ζ, the number of expected resonances is L/ ζ, where L is the total length of the IDT ($N_{periods}\lambda_{IDT}$). By designing IDT structures with L = ζ, we can work in the single mode regime with measured Q_m~ 600. Further improvements in Q_m can be achieved by apodizing the electrode geometry to achieve a 1D phononic crystal, and we expect to push the Q_m beyond 1000 soon.

CONCLUSIONS

We have demonstrated that a GaN HEMT platform is ideal for monolithic surface acoustic wave (SAW) filter integration. This exploits recent developments in improved RF GaN HEMT epitaxy (especially with thin buffer layers) and the availability of GaN foundry process which provide ready access to HEMT dies for post-processing. By exploiting the slow acoustic velocity in GaN compared to the substrate, significant energy localization (due to waveguiding effects) can be achieved leading to improved device performance.

ACKNOWLEDGEMENTS

KCB would like to acknowledge support from the European Research Council for project SBS 3-5. The fabrication and characterization work utilized facilities that were funded by the Engineering and Physical Sciences Research Council through the grant QuPIC. KCB would also like to thank Profs. John Haine, Mark Beach and Kevin Morris for valuable discussions.

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