

Article

Study of Acoustic Emission from the Gate of Gallium Nitride High Electron Mobility Transistors

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Abstract: Nitrides are the leading semiconductor material used for the fabrication of high electron mobility transistors (HEMTs). They exhibit piezoelectric properties, which, coupled with their high mechanical stiffness, expand their versatile applications into the fabrication of piezoelectric devices. Today, due to advances in device technology that result in a reduction in the size of individual transistor elements and due to increased structural complexity (e.g., multi-gate transistors), the integration of piezoelectric materials into HEMTs leads to an interesting occurrence, namely acoustic emission from the transistor gate due to piezoelectric effects. This could affect the device's performance, reliability, and durability. However, this phenomenon has not yet been comprehensively described. This paper aims to examine this overlooked aspect of AlGaN/GaN HEMT operation, that is, the acoustic emission from the gate region of the device induced by piezoelectric effects. For this purpose, dedicated test structures were designed, consisting of two narrow 1.7 μm -wide metallization strips placed at distances ranging from 5 μm to 200 μm fabricated in AlGaN/GaN heterostructures to simulate and examine the gate behavior of the HEMT transistor. For comparison, the test device structures were also fabricated on sapphire, which is not a piezoelectric material. Measurements of acoustic and electrical interactions in the microwave range were carried out using the “on wafer” method with Picoprobe's signal–ground–signal (SGS)-type microwave probes. The dependence of reflectance $|S_{11}|$ and transmittance $|S_{21}|$ vs. frequency was investigated, and the coupling capacitance was determined. An equivalent circuit model of the test structure was developed, and finite element method simulation was performed to study the distribution of the acoustic wave in the nitride layers and substrate for different frequencies using Comsol Multiphysics software. At frequencies up to 2–3 GHz, the formation of volume waves and a surface wave, capable of propagating over long distances (in the order of tens of micrometers) was observed. At higher frequencies, the resulting distribution of displacements as a result of numerous reflections and interferences was more complicated. However, there was always the possibility of a surface wave occurrence, even at large distances from the excitation source. At small gate distances, electrical interactions dominate. Above 100 μm , electrical interactions are comparable to acoustic ones. With further increases in distance, weakly attenuated surface waves will dominate.

Keywords: nitrides; piezotronics; high electron mobility transistors; piezoelectricity



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1. Introduction

Nitride semiconductors are an important part of high-frequency and high-power electronic devices, attracting considerable attention in both scientific research and industrial applications. These materials exhibit distinctive characteristics, such as high electron mobility, strong spontaneous and piezoelectric polarization, and good thermal stability, resulting in their integration into numerous high-performance devices. Over the last few decades, the superior properties of AlGaN/GaN high electron mobility transistors (HEMTs), such as high-speed operation, low noise, and high gain, have been used in

various applications, ranging from high-speed digital logic circuits to power amplifiers for mobile devices and satellite communication systems [1,2].

In addition, because of their high propagation velocities and sufficient piezoelectric coefficient, they are widely used in various MEMS devices that utilize acoustic waves. In practical applications, typically, modes other than basic Rayleigh modes are used, namely, Sezawa, pseudo-bulk, or bulk modes. In terms of applied designs, interdigital transducers [3,4] and layered resonators [5] are used to generate acoustic waves. Another dimension of complexity and opportunities stems from the fact that nitride layers are deposited on different types of heterostructure substrates, which creates opportunities for the additional modification of transducer characteristics by modifying the topology of the entire heterostructure, such as by adding additional grooves to increase their sensitivity [6] or by using a multilayer structure that supports more propagation modes compared to bulk materials. Another axis of development of nitride-based devices is the work on improving the operational parameters of semiconductor devices (e.g., HEMTs). To enable this, advancements in technology are required that result in shrinking the device's internal element dimensions and more complex device topologies (e.g., in multi-gate transistors). The combination of these two factors, the application of piezoelectric materials, such as nitrides, in the HEMT and more complex topologies of small dimension elements operating with higher frequencies, leads to an interesting occurrence, namely unexpected acoustic emission due to piezoelectric effects from certain areas of the semiconductor device. This phenomenon has the potential to affect the device's performance, reliability, and durability, especially during high-frequency operation. However, the precise mechanisms of how these effects appeared and their influence on HEMT operation remain inadequately examined and described, mostly due to the fact that the involved acoustic modes generated in such topologies usually are not in the form of pure modes. In earlier studies, it was found that the AC electric field induces an acoustic field in the nitride layer during gate control [7–9]. Such an acoustic field can propagate throughout the sample because of the low reflectance at the interface of the nitride layers and substrate. The acoustic wave propagates with low losses in the sapphire substrate and will be completely reflected at its boundary. This results in the possibility that it may return to the heterostructure region at a location that is difficult to predict. Such a residual acoustic field can, through piezoelectric generation, locally influence the operation of other semiconductor devices fabricated within the same substrate, especially in the case of monolithic microwave integrated circuits (MMICs). In article [9], measurements were made on the interaction of transistor gate structures with a SAW interdigitated transducer (IDT). The coupling between the HEMT transistor fabricated in the AlGa_N/Ga_N heterostructure and the interdigitated converter was demonstrated at frequencies corresponding to the IDT resonant frequencies. Further studies consider the use of electric fields and the manipulation of 2DEG parameters for non-reciprocal transducers, as well as the amplification of the acoustic signal [10]. Most of the previous studies focus on interactions between typical MEMS devices, e.g., interdigital transducers or film bulk acoustic resonators (FBARs), and semiconductor devices. Because of this, the examined acoustic modes in such cases are limited to those that are compatible with a particular transducer. However, the HEMT gate itself is a wide-band transducer, which, especially considering the existence of high-electric fields in the control area of the transistor, can emit and receive acoustic waves. Thus, in this study, the method used assumes the use of the layout of test structures resembling elements of AlGa_N/Ga_N HEMTs for RF amplification and switching. This allows the full extent of all possible modes to be observed during device operation. A comprehensive analysis of the acoustic emission from the gate of the AlGa_N/Ga_N HEMT transistor and possible interferences in the case of complex topologies is lacking in the literature. The main goal of this study was to investigate the phenomenon of acoustic waves emitted by a single transistor gate and the extent of that effect. This interference will influence the operation of HEMT transistors and MMICs fabricated in AlGa_N/Ga_N heterostructures and must be taken into account in their design, especially in cases requiring high isolation between individual blocks or circuit elements.

2. Materials and Methods

2.1. Fabrication of Dedicated Test Structures

To examine the acoustic emission from the HEMT gate, dedicated test structures were designed, consisting of two narrow ($1.7\ \mu\text{m}$) metallization strips corresponding to HEMT gates placed at distances, d_t , from $5\ \mu\text{m}$ to $200\ \mu\text{m}$. They were fabricated in an AlGaIn/GaN HEMT-type heterostructure. The gate width was the result of a standardized UV lithography process used for regular HEMT fabrication [11]. The range of distances between gates was selected based on the available dimensions of measurement equipment. To distinguish piezoelectric effects from pure electric field (capacitive) interference, test device structures with exactly the same layout and parameters were also fabricated on a clear sapphire substrate, which is not a piezoelectric material. Measurements of test device structures' acoustic and electrical interactions in the microwave range were carried out using the "on-wafer" method with Picoprobe's signal-ground-signal (SGS)-type microwave probes. An optical image of the structure ($d_t = 200\ \mu\text{m}$) is presented in Figure 1a, and the structure layout ($d_t = 50\ \mu\text{m}$) is presented in Figure 1b.

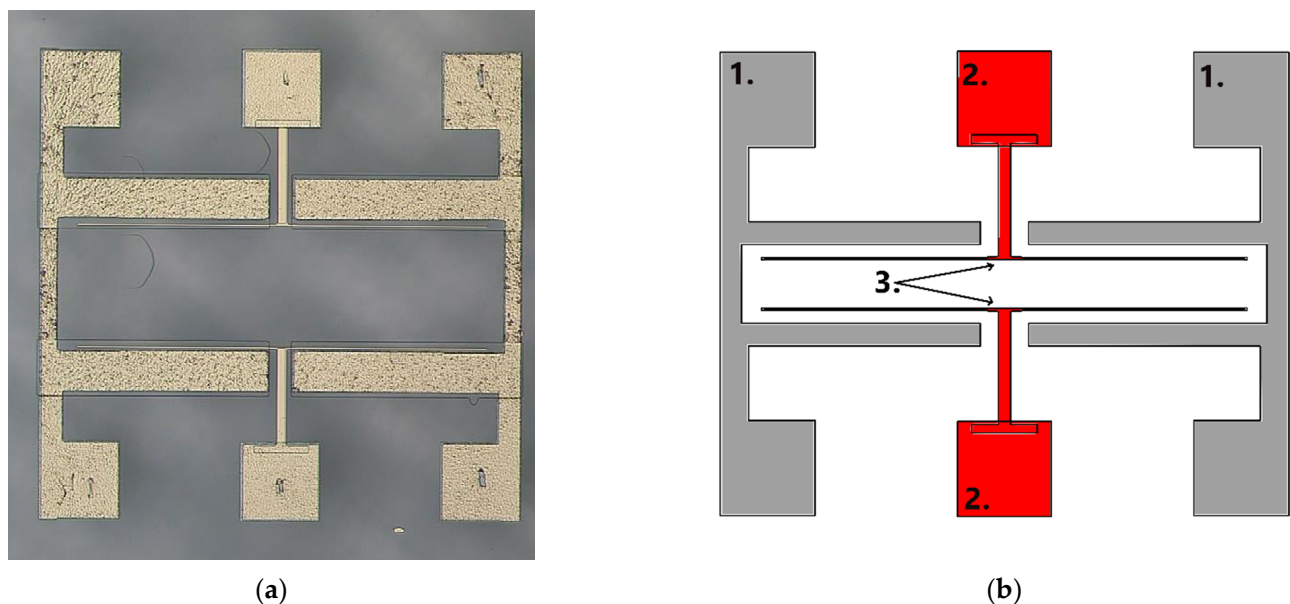


Figure 1. (a) An optical image of the structure used for the examination of acoustic gate emission in HEMT (b) Schematic layout of the structure, 1—ground area, 2—measurement probe pad connecting gate, 3—gate area.

The gates were surrounded by common ground. The connections layout was adjusted for the signal-ground-signal (SGS) measurement probes with a pitch of $250\ \mu\text{m}$. The ground lines were made wider to reduce resistance and provide insulation for the electrical field. A schematic cross-section of the test structure is presented in Figure 2a, and an HEMT-type heterostructure layer topology is presented in Figure 2b.

Seven structures with different d_t were fabricated. These were operated with an AC voltage generated between the electrodes and the ground using blade probes applied to the ohmic contacts. The distance between the ohmic contact and the gate was $d_g = 4\ \mu\text{m}$. The ground areas were interconnected. The structures were fabricated in AlGaIn/GaN HEMT heterostructures grown on a two-inch sapphire substrate using the metalorganic vapor phase epitaxy (MOVPE) technique in the AIXTRON $3 \times 2''$ CCS system. A very thin (approximately $2\ \text{nm}$) AlN layer was deposited on a $2060\ \text{nm}$ -thick GaN buffer layer on a sapphire substrate. This was followed by an AlGaIn layer with an aluminum content of $x = 25\%$ and a thickness of $20\ \text{nm}$. The middle part of the AlGaIn layer ($10\ \text{nm}$) was doped with Si to achieve an electron concentration of $3 \times 10^{18}\ \text{cm}^{-3}$ [12]. This combination of layers forming a heterostructure is the same set used for the fabrication of microwave

HEMTs [13–15]. In the same way, the gate contact was fabricated in a process with the same parameters that were typically used to fabricate the HEMT device. The Schottky contact representing the HEMT gates was made using Ru/Au double-layer metallization (30/180 nm). The ohmic contact (common mass surrounding gates) was made using Ti/Al/Mo/Au multilayer (20/100/45/190 nm) annealed using rapid thermal processing (RTP) for 30 s at nitrogen ambient at 820 °C. Additionally, the pads for SGS probes and connection lines were thickened with Ti/Au metallization layers (20/150 nm) [16,17].

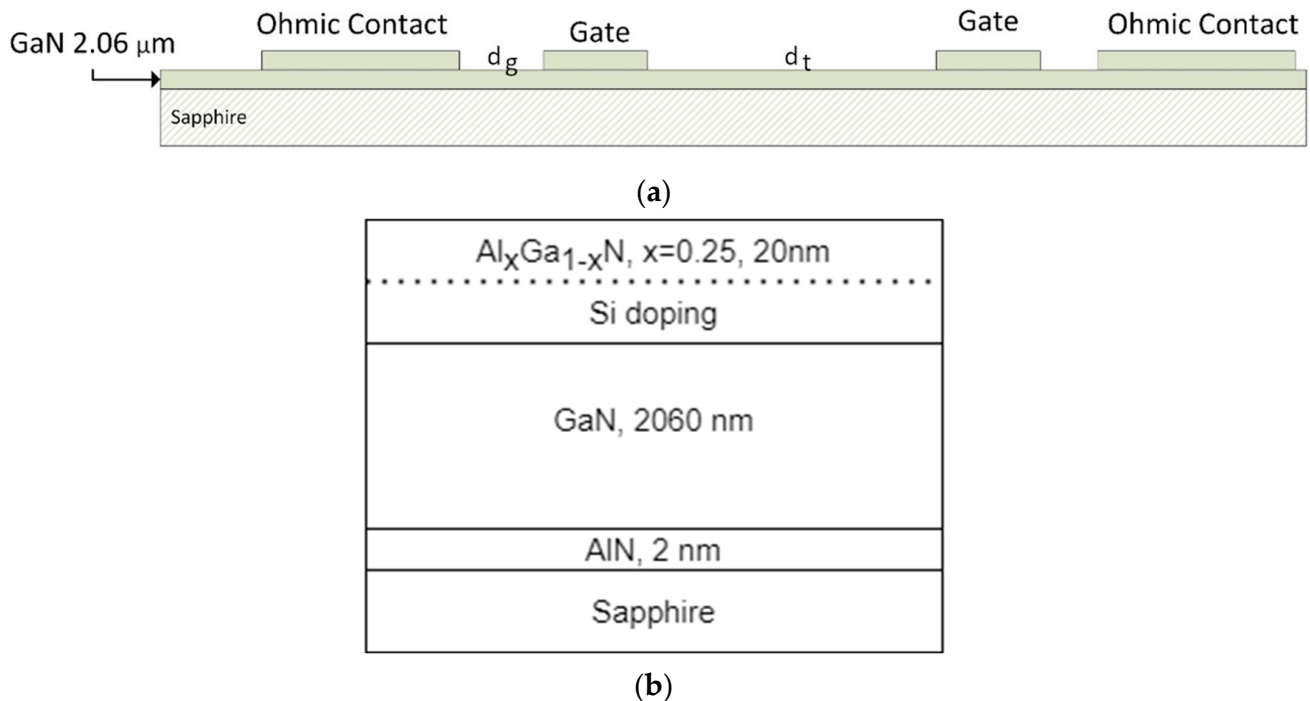


Figure 2. (a) Cross-section of the test structure showing the arrangement of gates and ohmic contacts. Distance $d_g = 4 \mu\text{m}$, distance $d_t = 5\text{--}200 \mu\text{m}$; (b) layers layout of HEMT-type AlGaIn/GaN heterostructure.

2.2. Microwave Measurements

Measurements of device test structures to examine the acoustic and electrical interactions in the microwave frequencies range were carried out using the “on-wafer” method with Picoprobe’s SGS-type microwave probes with a contact field distance of 250 μm. A four-port N5230A network analyzer (PNA-L Network Analyzer) from Agilent with HUBER+SUHNER Sucoflex 100 measurement cables was used. A proprietary Picoprobe ceramic substrate with CS-8 calibration structures was used to calibrate the network analyzer. Measurements were performed in the broad (fast scan) frequency range of 100 MHz–6 GHz and in narrower ranges corresponding to the specific types of generated acoustic waves. The device’s test structures and measurement probes were placed in a Cascade Microtech MPS150 measurement bench. The use of high-precision (200 revolutions/inch) 3D positioners magnetically mounted on drop-down platforms allowed for repeatable measurements. The measurement probes were positioned on a buffer layer at a distance of 2 mm. The main challenge with the measurements was ensuring accuracy. The gate of the transistor consists of the wide-band transducer, and as a result, the transmittance peaks observed at resonant frequencies ranged between −30 dB and −70 dB. The subtle nature of the transmittance spectra required measurements at a large number of frequency points (1600 points in the band from 100 MHz to 1.2 GHz) in the limited detector bandwidth of the network analyzer. Narrowing the detector bandwidth and increasing the number of measurement points resulted in a significant increase in measurement time. An acceptable compromise between measurement time and noise level was obtained with a detector bandwidth of 200 kHz and a measurement signal power of 0 dBm. Obtaining the correct and reliable measurement

results required a meticulous procedure for preparing the measurement setup. Before starting the measurements, the network analyzer, located in an air-conditioned housing, was warmed up for about 2 h. All measurement cables were protected against accidental displacement and deformation. This was followed by a calibration procedure using the short, open, load, through (SOLT) method with the additional option of “Isolation”. After such preparation, measurements of the tested structures could be performed in a reproducible way. Due to the drift of the measuring system, slight distortions appeared in the measured characteristics after approximately two hours, which did not affect the correct interpretation of the measurement results. An acceptable calibration accuracy was maintained for several days, provided the measuring system was adequately warmed up and the room temperature remained constant.

3. Results

Figure 3a,b shows the dependence of the transmittance $|S_{21}|$ as a function of frequency for the gate distance $d_t = 200 \mu\text{m}$ fabricated in an AlGaIn/GaN/sapphire heterostructure (red line) and sapphire (black line). The dependence, as a function of frequency and the transmittance $|S_{21}|$, was investigated, and the coupling capacitance, as a function of distance and calculated for two series of reference test structures fabricated in sapphire, was determined. The basic transmittance characteristic of both types of structures is similar and is mainly influenced by capacitive coupling. Figure 3c shows the dependence of the coupling capacitance as a function of distance, d_t , calculated for two series of reference test structures fabricated in sapphire. The measurements for samples with the AlGaIn/GaN heterostructure were almost the same. The thin heterostructure layers, even consisting of 2-DEG, do not influence the capacitance of the given sample. It is influenced mostly by the electrode layout (distance between gates) and the medium surrounding the sample, which are the same for both types of samples. It was calculated based on the matching of measurement characteristics with the equivalent circuit simulations described below. The value of this capacitance, assumed to be constant in the measurement frequency range, is responsible for the slope of the monotonic increase in transmittance from 0.1 GHz to 1.5 GHz. To confirm this assumption, a comparison of measured and simulated transmittances was performed for structures with different gate distances, d_t . The results are presented in Figure 3d. As can be seen, in the 0.1–1.5 GHz range, the measured transmittance matches well with simulations of equivalent circuits consisting of a parallel capacitive element with a value the same as in Figure 3c.

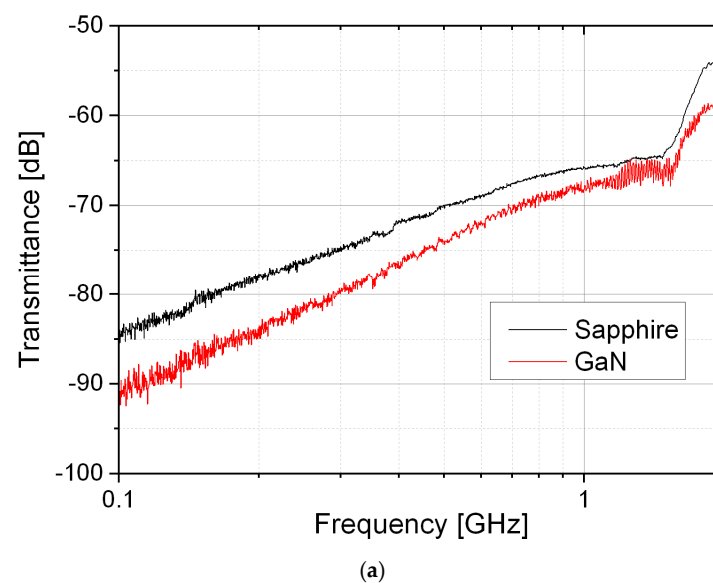


Figure 3. Cont.

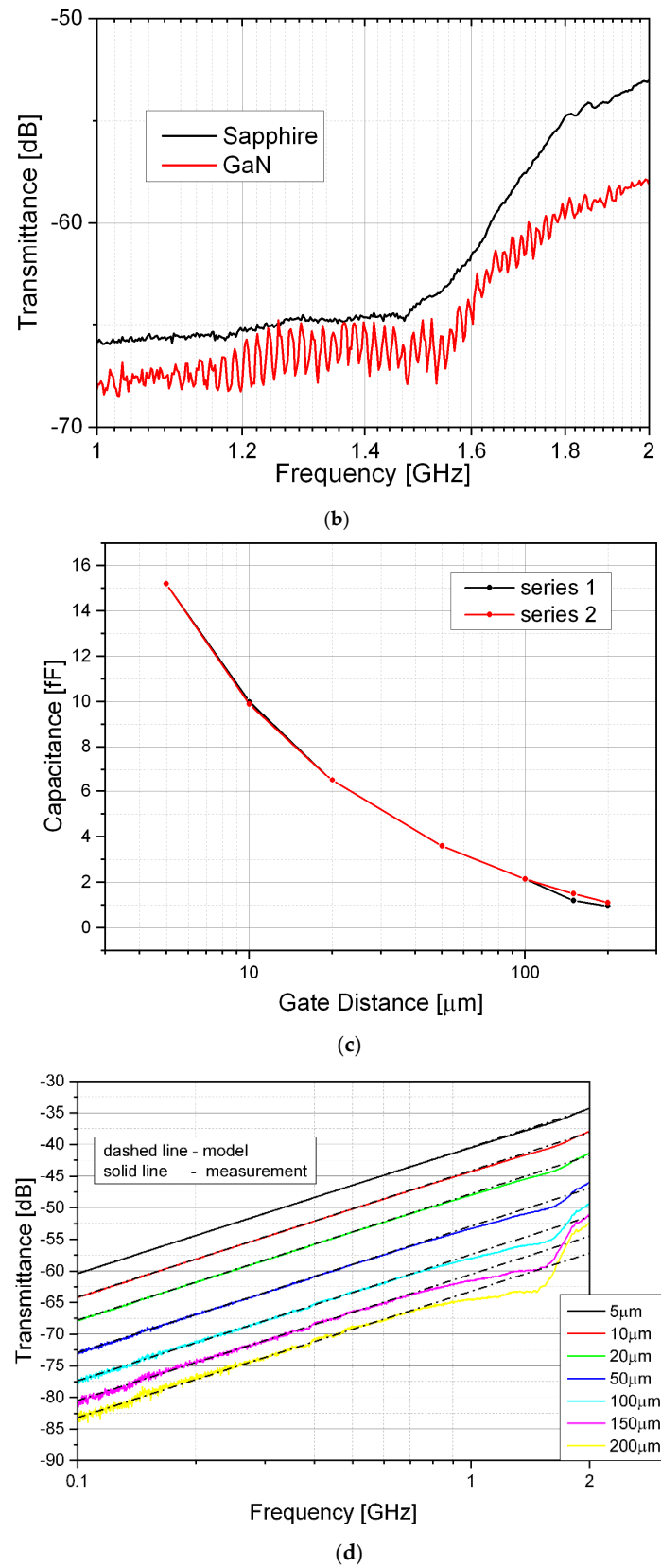


Figure 3. (a) Dependence of reflectance $|S_{11}|$ and transmittance $|S_{21}|$ vs. frequency for gates 200 μm apart fabricated in AlGaIn/GaN/sapphire heterostructures and in sapphire in the range 0.1–2 GHz and (b) in the range 1–2 GHz. (c) Dependence of coupling capacitance vs. distance between gates calculated for two series of reference test structures fabricated in sapphire. (d) Measured and simulated transmittance for different distances d_t in the range of 0.1–2 GHz.

In Figure 3a, a monotonic increase in transmittance values from -93 to -57 dB can be observed for a structure with $d_t = 200$ μm . The measured characteristic waveform shape is caused by the capacitive interactions, as suggested by the exact same shape for structures fabricated on the clear sapphire substrate. Particularly interesting is the presence of saw-like oscillations in higher frequencies. They are only present for test structures with piezoelectric layers. The main difference between the measured test devices appears at frequencies above 1 GHz. For structures made in the AlGaIn/GaN heterostructure, oscillations can be observed (Figure 3b). As these do not occur for structures fabricated on sapphire, it can be assumed that they are the result of piezoelectric interactions. In addition, they have the character of interference between electrical and acoustic interactions, considering that the observed oscillations vary in amplitude with small changes in frequency, which is a result of successive resonances of the propagated acoustic wave with a specific phase velocity. The whole transmission characteristic can be described as a combination of a capacitive component (constant phase shift) and an acoustic component with variable phase. To determine the phase velocity of the acoustic wave propagation, the phase variation of the wave as a function of the distance between the electrodes has to be analyzed. The propagation of an acoustic wave on the surface between the electrodes can be described by the dependence [18] (1), as follows:

$$A = A_0 \sin\left(\omega\left(t + \frac{x}{V_p}\right)\right) \quad (1)$$

where A and A_0 describe the amplitude of the wave, ω represents the frequency, t represents time, x represents the position in space, and V_p represents phase velocity.

It follows from the above equation that the phase difference of a wave with the same phase velocity, V_p , but with different frequencies, ω_1 and ω_2 , over a segment of length d is (2), as follows:

$$\Delta\phi = (\omega_1 - \omega_2) \frac{d}{V_p} = \Delta\omega \frac{d}{V_p} \quad (2)$$

With a phase change in the acoustic wave of 2π , the transmittance values of S_{12} and S_{21} coincide. Figure 4a shows the equivalent electric model of the tested structure and the simulation result. The upper diagram represents measurement data loaded from a file (red line in the corresponding Figure 4b presenting the simulation results), and the lower diagram represents the equivalent circuit consisting of the capacitance $C_1 = 0.6$ fF and voltage-controlled current source (VCCS) with transmittance $G = 0.6$ μAV^{-1} and propagation time t_p , as follows:

$$t_p = \frac{d_t}{V_p} \quad (3)$$

The later element, G , represents the acoustic interaction between transistor gates caused by piezoelectric coupling [19–21]. The exact values of these parameters are adjusted to fit the simulation curve to measurements (the characteristic slope is a result of the effect of the capacitance value and the transmittance value on the amplitude of the oscillations). This modeling approach allows for the estimation of two defining parameters, each one having a completely different impact on the measured characteristics. The process needs to be repeated for every measured characteristic. The match between estimated and measured capacitance values for different distances, d_t , is presented in Figure 3d. It can be observed that this single parameter is enough to explain most of the shape of the characteristic. In the case of the second estimated parameter, V_p , the saw-like oscillations are less visible for smaller d_t due to the higher capacitance of the sample. Because of this, for the estimation of the propagation speed of the wave that can cause such an effect, the biggest gate distance is selected. By matching the frequency of oscillations (using Equation (2)), the propagation speed, V_p , can be estimated. Compliance with simulated and measured characteristics at a distance of $d_t = 200$ μm was obtained for a propagation velocity of $V_p = 3435$ ms^{-1} . This relatively simple model consisting of only two elements reproduces the measured characteristic well.

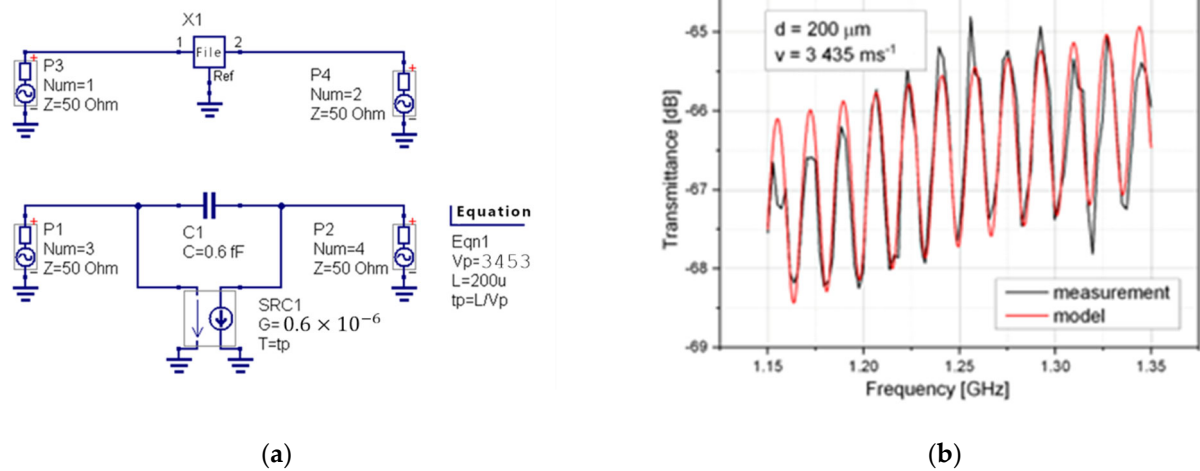


Figure 4. (a) Equivalent circuit of the test device structure and (b) result of simulation of the transmittance in 1.15–1.35 GHz range.

To determine the exact mode of the acoustic wave generated by the transistor, it is necessary to determine the KH factor—the product of wave vector K and layer thickness H . It normalizes the thickness of the layer and the magnitude of the wave vector to one value that is comparable among different layouts [22]. The factor is equal to (4), as follows:

$$KH = 2\pi f \frac{H}{V_p} \quad (4)$$

where H represents the thickness of the GaN layer (2.06 μm), and f represents the excitation frequency (1.15–1.35 GHz). For the measured structures and the analyzed case, the factor is equal to $KH = 4.21$ –4.94. For this value range, two types of modes (Rayleigh and Sezawa) can propagate in GaN on sapphire layers [22]. The Rayleigh mode in pure GaN has a propagation velocity of 3704 ms⁻¹; for GaN layers on sapphire, this value is correspondingly higher. Similarly, for this layer thickness ratio, the Sezawa mode has velocities close to the bulk transverse waves of sapphire (5700 ms⁻¹) and higher than the Rayleigh mode. The velocity estimated using the analysis of the transmission characteristic is 3435 ms⁻¹ and is much lower than the data in the literature for Rayleigh waves for GaN [7]. However, because it is the wave mode with the lowest propagation velocity out of all modes, it is correct to attribute it as the source of the observed interferences. Its lower speed in this case can be explained by the peculiarities of the heteroepitaxial GaN layers on sapphire used to fabricate HEMTs. They are highly defected, and their mechanical stiffness is much lower than that of pure GaN [14,23]. A detailed explanation of this effect will be presented soon [24].

Simulations of Acoustic Wave Propagation

To explain and analyze the acoustic interference between transistor gates the finite element method simulation was carried out using Comsol Multiphysics software. The main aim is to prove that the single HEMT gate via the polarization of the GaN layer is able to induce a surface wave that will propagate in relatively long distances (relative to the distance of significant electric field interactions). Additionally, considering that the gate is a wide band transducer simulation should explain why the Rayleigh acoustic wave is observed only in a certain frequency range. Simulations were performed on a 2D half-plane structure cross-section. The model applied was a linear piezoelectric model, which in stress-charge form, is described by a set of Equations (5) and (6) [25], as follows:

$$T = cS - eE \quad (5)$$

$$D = eS + \epsilon_0\epsilon_r E \quad (6)$$

where S represents strain, T represents stress, E represents the electric field, D represents the electric displacement field, c represents material stiffness, e represents the piezoelectric coefficient, ϵ_0 represents the permittivity of free space, and ϵ_r represents relative permittivity. Material data used in simulations are material data selected based on the literature [7,26,27] and are presented in Tables 1 and 2. The calculations should provide complete wave distribution (strain state) in the whole structure without any periodicities. It is more challenging compared to typical simulations of acoustic wave interactions, in which symmetries and periodicity, e.g., of interdigit transducers, allow for significant simplification of the structure. Additionally, the wide span of different dimensions should be considered. The relationship between the thickness of the GaN layer (2.06 μm) and structure (18 mm after being cut from 2" substrate) and the thickness of the sapphire (300 μm) is large and requires increasing the number of mesh elements to correctly simulate the wave distribution with submicrometer accuracy. To overcome the above limitations, the perfectly matched layer (PML) transformation was applied, which allows us to focus on the most significant area around the transistor gate. For further simulation simplification, the HEMT heterostructure was assumed to be modeled as a uniform GaN layer.

Table 1. Material data for GaN used in simulations.

Parameter	Tensor Element	Value
Stiffness, c_{ij} , [GPa]	c11	390
	c33	398
	c44	105
	c12	145
	c13	106
Piezoelectric Coefficient, e_{ij} , [cm^{-2}]	e_{16}	−0.3
	e_{31}	−0.289
	e_{33}	0.464
	ϵ_{33}	11.65
	ϵ_r	8.9

Table 2. Material data for sapphire used in simulations.

Parameter	Tensor Element	Value
Stiffness, c_{ij} , [GPa]	c11	490
	c33	492
	c44	146
	c12	165
	c13	114
	c14	−23
Relative permittivity, ϵ_r	ϵ_r	9.4

Figure 5a–c show the simulated distribution of the total displacements induced by a single gate in the tested device structure for three different frequencies (1.2 GHz, 2.4 GHz, and 5.6 GHz).

At frequencies below 1 GHz, the GaN layer was too thin compared to the acoustic wavelength to form a significant acoustic wave interaction. Around 1.2 GHz, the optimal ratio of electrode dimensions, the GaN layer thickness, and the Rayleigh wavelength allow for optimal wave induction and its good propagation, allowing for interference with other HEMT gates, which was visible in electrical transmittance measurements of the test structures. At a frequency of 2.4 GHz, the dispersion and drop in amplitude of the surface waves propagating laterally can be observed due to the length of the wave equal to the factor of GaN thickness. In this frequency, the presence of surface waves (resulting in a saw-like shape of characteristic) was not observed in the electric measurements, probably due to too high noise and too small instrument accuracy. At even higher frequencies, the resulting distribution of displacements due to numerous reflections and interferences becomes complicated and is not able to form significant surface waves that can influence other elements.

Performed simulations explain why the effect of acoustic wave interferences between HEMT gates was observed for a particular frequency range. Another conclusion is that there is always the possibility of a surface wave, even at large distances from the excitation source. At small distances between gates, electrical interactions dominate. Above 100 μm , electrical interactions are comparable to acoustic ones. With further increases in distance, the weakly attenuated surface waves became the main component of unpredictable interferences.

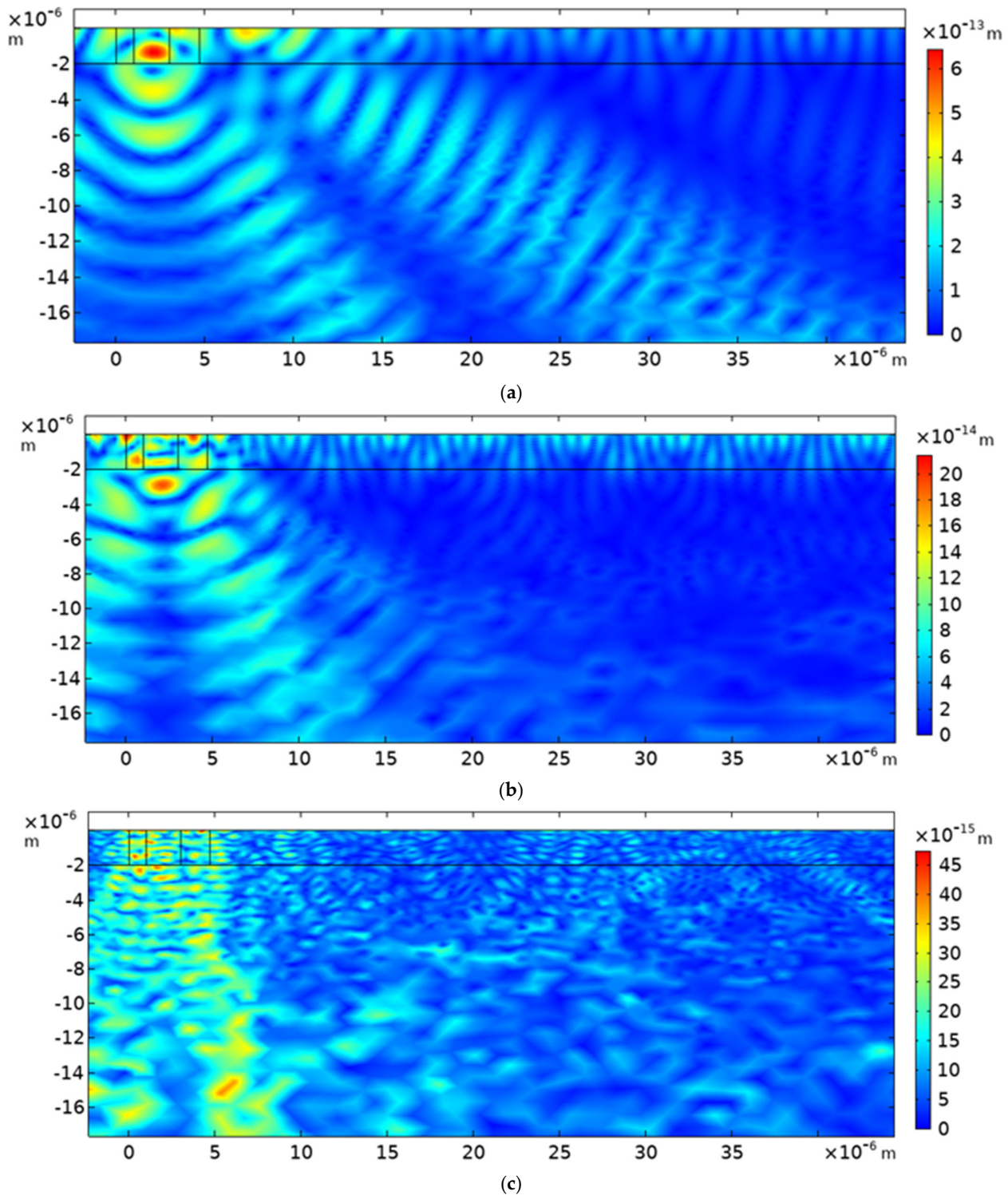


Figure 5. Simulated distribution of total displacements induced by a single gate in the tested device structure as a function of frequencies: (a) 1.2 GHz, (b) 2.4 GHz, and (c) 5.6 GHz.

4. Summary

The results of the measurements and simulations performed clearly show that the possibility of uncontrolled acoustic wave propagation in the microwave range of the L- and S-bands (possibly also in the C-band) should be taken into account during the design of HEMT transistors and MMICs fabricated in AlGa_N/Ga_N heterostructures, especially in situations requiring high isolation between individual blocks or circuit elements. It was observed that at frequencies up to 2 GHz, the formation of volume waves and a surface wave, capable of propagating over long distances (in the order of tens of micrometers) occurred. Although the resulting distribution of displacements becomes complicated at higher frequencies due to numerous reflections and interferences, there is always the possibility of surface wave appearances, even at large distances from the excitation source. Electrical interactions dominate at small gate distances. If the distance exceeds 100 µm, electrical interactions are comparable to acoustic ones. With further increases in the distance, weakly attenuated surface waves will dominate.

The selected design of test structures consisting of single HEMT gates that form a wide-band transducer allows for holistic observations. The advantage of this method over previously presented methods utilizing specialized test structures in the form of, e.g., interdigit transducers is that it is capable of observing various acoustic modes, including those that are not coupling to typical transducers (due to different acoustic wave polarizations). A further rise in demand for devices with a higher frequency of operation and better performance can be expected and will require shrinking the device size and the development of more complex topologies. To fulfill this requirement, a proper understanding and methodology of predicting low-level acoustic wave interaction with internal HEMT elements is essential, as they can produce unpredictable side effects.

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Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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