Pseudo-bulk SAW transducers fabricated in GaN epitaxial layers grown on sapphire substrate

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Abstract. Gallium nitride is a material commonly applied to the fabrication of various semiconductor devices, naming High Electron Mobility Transistors (HEMT) and Light Emitting Diodes (LED). Its unique feature is that it also possesses good piezoelectric properties. This enables to produce devices that integrate both active transistor operation and signal processing and filtration in one monolithic chip. This aim requires a comprehensive analysis of the acoustic wave propagation in the gan/sapphire system. Particularly attractive in the construction of modern acoustic instruments, due to higher propagation speeds, is the utilisation of pseudo-bulk modes. This paper presents the results of research on Surface Acoustic Wave (SAW) transducers using pseudo-bulk waves propagating in thin (2-6 μm) layers of GaN on sapphire. The layers were made by the MOVPE process using a low-temperature buffer layer. Transducers with a two-finger pitch of 9 and 18 μm with 48 and 24 periods respectively were made using electron lithography. Low finger resistivity was achieved by using Ru/Au/Ti/Au metal alloy. The results of microwave measurements identifying particular pseudo-bulk mods and their dispersion characteristics are presented. Two pseudo-bulk mods were observed, the first one with a propagation velocity range of 8500-7800 ms⁻¹ and the second one of 7200-7300 ms⁻¹. Additionally, pseudo-bulk modes were also compared with classical Rayleigh modes generated in the same transducers at lower frequencies. The results are important from the point of view of possible monolithic integration of the tested transducers with High Electron Mobility Transistors.

1. Introduction
The research on gallium nitride (GaN) layers grown on the sapphire substrate is one of the main directions of the development of modern piezoelectric devices such as filters, resonators, and MEMS Lab-on-chip [1–5]. This is due to the unique properties of nitride materials. Gallium nitride has strong piezoelectric properties. The piezoelectric coefficient of gallium nitride is equal to 0.3-0.8 cm²/V and is oriented along the C crystallographic axis, the same as the epitaxy growth direction [6,7]. Besides, gallium nitride has good semiconductor properties and, in combination with other nitride layers, allows for the formation of heterostructures with a localised two-dimensional electron gas (2DEG) [8]. This enables the fabrication of High Electron Mobility Transistors (HEMT), which are widely applied for both microwave and high-power devices. The manufacturing process of SAW transducers in GaN layers is compatible with that of the transistors [9], which makes SAW transducers, fabricated in GaN layers, attractive for the filtering and signal processing application. Such devices could be monolithically integrated with the amplifier system. The GaN interdigital SAW transducers, unlike SAW fabricated in...
other classical piezoelectric materials such as PZT or quartz, allow the generation and detection of a wide range of acoustic surface modes [10,11]. This is a consequence of the propagation of the acoustic waves in a multilayer system. The acoustic waves, that are formed as a result of piezoelectric interaction in the GaN layer, propagate partially in a sapphire substrate that has a lower density and higher rigidity. This results in the occurrence of typical piezoelectric mods with real components of k-wave vectors (Rayleigh mods and Sezawa mods) as well as mods whose propagation vectors are imaginary. Such mods are called pseudo-bulk waves. The principle of their propagation and their propagation velocity is an intermediate state between the Rayleigh and Sezawa surface wave propagation and bulk waves [12]. Similarly, to surface waves they propagate along the surface and disappear within the depth of the layer. However, their propagation velocity is between the transverse propagation velocity of a bulk wave in sapphire (6000-7000 m/s), through the velocity of a longitudinal bulk wave in GaN (7500-8000 m/s) to the velocity of a longitudinal wave in sapphire (11 000 m/s) [13]. The mechanism of pseudo-bulk wave propagation is based on the fact that vertical deformations of the GaN layer translate into three waves: one longitudinal and two transverse. The longitudinal wave propagates deep into the ground, where the transverse waves propagate in the direction parallel to the GaN layer. Due to the similarity of the acoustic impedance values of the GaN layer and the sapphire substrate, the emerging waves for most frequencies will disappear into the substrate, propagating as bulk waves. However, at certain frequencies, the overlapping of longitudinal and transverse waves, the interaction between the layers and the transducer fingers will result in a longitudinal wave with a propagation angle slightly deviating from the surface. This results in the propagation of a surface wave, as the radiation of energy to the ground is small enough to cause the disappearance of the amplitude of wave vibrations at a distance of several wavelengths away from the surface. At the same time, their wave phase velocity is higher than the sapphire transverse bulk wave velocity. This makes pseudo-bulk modes interesting from the point of their application for SAW transducers, as they allow to obtain higher transducer operating frequencies at the same electrode spacing.

This work presents the results of microwave measurements of the interdigital transducers fabricated in GaN layers, of three different thicknesses (2 μm, 4 μm and 6 μm) grown on sapphire by MOVPE method (Metal Organic Vapour Phase Epitaxy). The details of the growth process may be find in other papers [14] and the induced pseudo-bulk waves were analysed and identified for the SAW transducers application.

2. Experiment
In order to obtain pseudo-bulk surface waves, interdigital transducers were fabricated with finger spacing λ= 9 and 18 μm. They had 48 and 24 periods, respectively. The transmitting and receiving transducers were symmetrical. The distance between the transmitters was 5 mm. Figure 1 shows an optical image of the transmitters’ structures (a) and magnification of the essential parts (b).

![Figure 1. Optical image of fabricated interdigital transducers (a) with the magnification presenting its fingers (b).](image-url)
The topology of the fabricated transducers was adapted for microwave measurements performed with the GSG (Ground-Source-Ground) microwave “on wafer” probes. The distance between the coplanar tips of the probes was \(2 \times 250\mu\text{m}\). Figure 2 shows an optical image of the evaluated transducer.

![Figure 2. Optical image of the transducer during the measurement performed with the use of “on wafer” microwave probes.](image)

The transducers were fabricated in AIIIN heterostructures grown by the MOVPE technique on sapphire substrates [9]. The transducers were fabricated in the layer which is the basic part of the HEMT heterostructure – an undoped GaN buffer layer of three different thicknesses: 2 \(\mu\text{m}\), 4 \(\mu\text{m}\), and 6 \(\mu\text{m}\). The GaN layer was grown at a low temperature (650°C) buffer GaN layer. The growth was carried out on two-inch sapphire substrates of orientation (0001) using AIXTRON CCS 3x2” epitaxial system. The TMGa and NH \(_3\) were used as the source. The crystallisation process was performed in a hydrogen atmosphere under the pressure of 100 mbar. A set of dedicated photolithographic masks containing the test devices was designed and manufactured using electron lithography [15–17]. The transducers electrodes were fabricated by the lift-off of Ru/Au/Ti/Au metallisation [18]. Table 1 presents a detailed list of fabricated transducers, that were fabricated in GaN layers of three different thicknesses of 2 \(\mu\text{m}\), 4 \(\mu\text{m}\), and 6 \(\mu\text{m}\) and have two different finger spacings (9 and 18 \(\mu\text{m}\)).

| Sample       | Thickness [\(\mu\text{m}\)] | \(\lambda\) [\(\mu\text{m}\)] |
|--------------|-----------------------------|-------------------------------|
| Sample #1    | 2                           | 9                             |
| Sample #1    | 2                           | 18                            |
| Sample #2    | 4                           | 9                             |
| Sample #2    | 4                           | 18                            |
| Sample #3    | 6                           | 9                             |
| Sample #3    | 6                           | 18                            |

### 3. Results and Discussion

Figure 3 presents the measured transmittance and reflectance characteristics of the pseudo-bulk mode. Transducer with the 18 \(\mu\text{m}\) finger spacing fabricated in the GaN layer of the thickness of \(h = 2 \mu\text{m}\).

The measured spectra have a broadband character, resulting from a wide range of permitted solutions adapted in phase to the dimensions of the transducer and their character, being a composition of longitudinal and transverse bulk mods. In order to compare the selectivity of the transducer in Figure 4, the Rayleigh mod characteristics measured for the same sample are shown.
Figure 3. Transmittance and reflectance of the transducer with 18 μm finger spacing fabricated on 2 μm GaN layer in the pseudo-bulk mode area.

Figure 4. Transmittance and reflectance of the transducer with 18 μm finger spacing fabricated on 2 μm GaN layer in the Rayleigh mode area.

It was observed that the pseudo-bulk mod shows vastly superior coupling to the interdigital transducer, assessed by a greater negative change in reflectance. At frequencies corresponding to Rayleigh’s mod the difference, $\Delta S_{11}$, is equal to 0.05 dB while for the pseudo-bulk mod the difference, $\Delta S_{11}$, is equal to about 0.3 dB. Similarly, the pseudo-bulk mode is characterised by a considerably higher transmittance value between transducers concerning Rayleigh’s mode: -35 dB and -50 dB, respectively. The bulk mod generated in a transducer with a specific electrode spacing allows for the higher operating frequencies, better transmission, and better electrical coupling than the Rayleigh mod, rendering it to be more suitable for device application. Although, it must be noted that pseudo-bulk modes have lower selectivity that translates into a lower quality factor of resonators based on them.
Rayleigh’s and Sezawa modes, the pseudo-bulk modes in layered systems are dispersive. Their propagation speed strongly depends on the value of the KH coefficient. It is a product of wave vector $K$ and layer thickness $H$. The wave vector for given transducer results from the spacing of its finger, $\lambda$, (equation 1):

$$k = \frac{2\pi}{\lambda}$$  \hspace{1cm} (1)

The application of the normalised KH coefficient enabled the comparison of transducers, with varying finger spacing, fabricated on layers of different thicknesses. For a sufficiently large value of the coefficient, there may exist several pseudo-bulks modes differing in propagation velocity for given layer thickness and finger spacing. According to dispersion characteristics of GaN layers grown on sapphire discussed in the work [18] such a situation occurs for $KH > 2$. Figure 5 presents transmittance and reflectance characteristics of a transmitter with finger spacing, $\lambda = 9 \, \mu m$, fabricated in a layer of $h = 6 \, \mu m$ ($KH = 4.18$) in the range of pseudo-bulk mods.

Two pseudo-bulk modes with the phase velocity of $V_p = 7280 \, ms^{-1}$ and $V_p = 7857 \, ms^{-1}$ respectively can be observed. The coefficients $S_{11}$ and $S_{22}$ that describe the energy absorption by the transmitter are continuous and no separation occurred into two modes, but the characteristics of the coefficients $S_{21}$ and $S_{12}$ clearly show the existence of two separate maxima. Analysis of the frequencies for which there are transmission maxima enabled to determine and distinguish the propagating modes and to determine their phase velocity speed. The relationship between finger width, $\lambda$, frequency of occurrence of a given maximum, $f_{max}$, and phase velocity of a given $V_p$ mode describes the relationship 2:

$$V_p = \lambda f_{max}$$  \hspace{1cm} (2)

Figure 6 shows the calculated velocities dependences of individual modes on the KH coefficient for all observed pseudo-bulk modes for all measured samples.
It was observed that depending on the thickness of the GaN layer in which the transducers were fabricated, the propagation velocity of the modes is varying, and it decreases with the increasing of layer thickness. This is due to the higher stiffness and lower density of the sapphire substrate in comparison to the GaN layer. For 2 μm layer for a given finger spacing (9, 18 μm) there was only one pseudo-bulk mode, for 4 μm and 6 μm layers for a given transducer spacing there were two propagation mods: pseudo-bulk high-speed (PB M1) and pseudo-bulk low-speed (PB M2). Figure 7 presents the distribution of both mods depending on the KH coefficient.

**Figure 6.** Identified pseudo-bulk modes phase velocities in the function of KH coefficient.

**Figure 7.** Dependence of two existing pseudo-bulk modes phase velocities on the KH coefficient.
The higher speed mod (PB High-Speed) propagates at a velocity close to the longitudinal wave propagation velocity in GaN (8045 ms\(^{-1}\)). Its speed is strongly dependent on the KH coefficient and is between 8400 to 8000 ms\(^{-1}\). The slower pseudo-bulk mode propagates at 7200 ms\(^{-1}\) and its propagation speed does not depend on the KH coefficient. The limit value of the coefficient for which the two modes exist is 1.3. It is lower than the literature data would indicate [13]. This is probably due to the specificity of the GaN layer growth process on the sapphire substrate with the low-temperature buffer layer that must be applied to obtain a planar continuous high-temperature GaN layer of required thickness. Its presence results in a strongly deformed interface with lower rigidity.

4. Conclusions
The developed transducer design, fabricated in a technology compatible with the HEMT technology, enables the processing and filtering of signals in a wide range of frequency depending on the finger spacing of the transducer and thickness of layers in which the transducer is made. Two pseudo-bulk modes may propagate in layers of typical thicknesses applied in the manufacturing of HEMT transistors in transducers with finger spacing from the 10 μm to 20 μm range. Both can be used for transducer design, with the slower mode exhibiting no dispersion, making it more advantageous for application, despite its lower frequency obtained from the same pitch in the transducer design. It is caused by its lower sensitivity to inevitable fluctuations of the epitaxy process. The results presented in this paper show the possibility of application of the pseudo-bulk SAW modes, generated in thin GaN layers, for the development of efficient signals processors integrated monolithically with active transistor elements in the same substrate [5,19].

Acknowledgments
This work was co-financed by the National Centre for Research and Development under grants: LIDER VIII project no. LIDER/24/0137/L-8/16/NCBIR/2017 and TECHMATSTRATEG no. 1/346922/4/NCBIR/20177, Polish National Agency for Academic Exchange under the contract PPN/BIL/2018/1/00137, and Wroclaw University of Science and Technology subsidy. This work was accomplished thanks to the product indicators and result indicators achieved within the projects co-financed by the European Union within the European Regional Development Fund, through a grant from the Innovative Economy (no. POIG.01.01.02-00-008/08-05) and by the National Centre for Research and Development through the Applied Research Program Grant no. 178782 and Grant LIDER no. 027/533/L-5/13/NCBR/2014.

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