Acoustic plate modes in GaN crystal plates cut perpendicularly to crystallographic Z axis

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Abstract: The chosen parameters acoustic plate modes (APMs) in GaN crystal plates were calculated and measured. It was found that the spectrum of APMs consists of two areas. In the first area, just above the surface acoustic wave (SAW) passband, the insertion loss of APMs is much higher than in the SAW passband. In the second area, the insertion loss of APMs is decreased, reaching a minimum value at a frequency about two times higher than the resonance frequency of SAW. Because the energy of the longitudinal component of mechanical displacement in this mode is concentrated near both planes of the GaN plate, it can be used in APM sensors.

Key words: bulk GaN crystal, surface acoustic wave (SAW), bulk acoustic wave (BAW), acoustic plate mode (APM), interdigital transducer (IDT), SAW filter

Akustyczne mody płytowe w płytkach z kryształu GaN wyciętych prostopadle do osi krystalograficznej Z

Streszczenie: Obliczono i zmierzono wybrane parametry akustycznych modów płytowych (AMP) w płytkach z kryształu GaN. Stwierdzono, że spektrum AMP składa się z dwóch obszarów. W pierwszym obszarze, tuż powyżej pasma akustycznej fali powierzchniowej (AFP) tłumienność wtrąceniowa jest dużo wyższa w porównaniu do tłumienności w paśmie AFP. W drugim obszarze tłumienność wtrąceniowa AMP maleje osiągając wartość minimalną przy częstotliwości około dwa razy większej niż częstotliwość AFP. Ponieważ energia podłużnej składowej przemieszczeń mechanicznych tego modu jest skoncentrowana w pobliżu obydwu powierzchni płytki GaN, może być on wykorzystany w czujnikach z AMP.

Słowa kluczowe: objętościowy kryształ GaN, akustyczna fala powierzchniowa (AFP), akustyczna fala objętościowa (AFO), akustyczny mod płytowy (AMP), przetwornik międzypalczasty (PM), filtr z AFP

1. Introduction

Gallium nitride (GaN) epitaxial layers deposited on foreign substrates and GaN crystals can find application in such passive surface acoustic wave (SAW) components as bandpass filters [1]. Input and output interdigital transducers (IDT) are used in the filters for generation and detection of SAW and for shaping of the passband. However, besides SAW, bulk acoustic waves (BAWs) are also generated and detected at frequencies above the SAW filter passband [2]. BAWs are generated at the upper surface of the piezoelectric substrate and propagate along the surface and into the bulk of the substrate. When the bottom surface of the substrate is effectively moved to the infinity by an acoustic absorber, or when the upper and bottom surfaces are not parallel, slow quasishear, fast quasishear and longitudinal BAW propagate only along the surface of the substrate. BAWs directed towards the bulk of the substrate are eliminated. In practice, substrates are fabricated as plates with parallel upper and bottom surfaces for technical reasons. The bottom plane is usually stiffly mounted onto the seal wire. In this case, BAWs take the form of a spectrum of acoustic plate modes (APMs) due to reflections from parallel planes. APM velocities are ranged between slow quasishear and fast longitudinal BAW. Then, APMs disturb the higher stopband in a SAW bandpass filter. On the other hand APMs are attractive when applied in a piezoelectric sensor. APMs generated and detected at the bottom plane of the plate are sensitive to conditions at the upper plane. In this manner, electrodes are separated from harsh conditions. For higher sensitivity, the displacement energy of APMs should be concentrated at the upper and bottom plane. The velocities of APMs are the eigenvalues of a piezoelectric plate. The displacement energy distribution along the plate thickness is a function of velocity. It is the purpose of this report to present calculations and measurements of the chosen parameters of APMs in Z-cut GaN crystal plates.

2. Calculation results

In the case of GaN, APMs propagate in any direction perpendicular to the Z axis (Fig. 1) with the same parameters, because of acoustic isotropy in the 6 mm hexagonal crystallographic system [3].

APM parameters were calculated using the same algorithm and computer program as for APMs in YZ $LiNbO_3$ [4]. Using GaN, the physical constants determined in [3], SAW and APM velocities v_f and v_m for a free and metallized

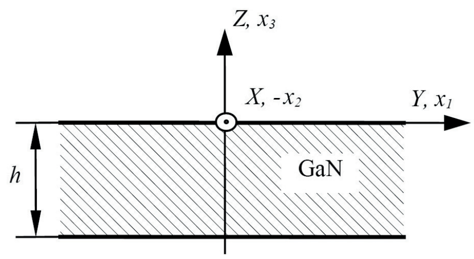


Fig. 1. A GaN plate and coordinate systems, X, Y, Z – crystallographic axes, x_1, x_2, x_3 – axes for SAW and APM.
Rys. 1. Płytka GaN i układy odniesienia, X, Y, Z – osie krystalograficzne, x_1, x_2, x_3 – osie związane z AFP i AMP.

surface, respectively, and electromechanical coupling coefficients $K^2 = 2(v_f - v_m)/v_f$ were calculated (Fig. 2). Here, h/λ is the ratio of the GaN plate thickness h to the acoustic wavelength $\lambda(\lambda = 4p$, where p is the IDT electrode period), m is the mode identifier. For GaN, the velocity difference between the first APM ($m = 1$) and the SAW mode is equal to about 5.5 % of the SAW velocity. Above the mode free range (MFR), there are two areas of APMs in which a local maximum of K^2 exists. In the first area, from $m = 1$ to $m = 10$, K^2 is very small. For $m > 10$, K^2 is increased up to a maximum value at $m = 36$. Therefore, we can expect that a strong APM excitation will be present in this case. Fig. 3 presents the distributions of the relative amplitudes U_1 and U_3 of APMs, inside the GaN plate. It can be seen that for $m = 4$ and $m = 36$, transverse vertical and longitudinal components, respectively, are dominant. For $m = 36$, the amplitude of the longitudinal component U_1 of mechanical displacement is concentrated near both planes of the GaN plate.

3. Measurement results

A simple SAW filter consists of two identical IDTs deposited on a piezoelectric substrate (Fig. 4). Double - electrodes are usually used to eliminate reflections from the IDTs [1]. The following data were used for the filter: p = 8 μm ($\lambda = 4p$), W = 1.6 mm, d = 1.2 mm and N = 254, where p, W, d and N are the period of electrodes, aperture, distance between IDTs and number of electrodes in each IDT, respectively. The filter structure was deposited on a semi insulating GaN plate measuring 10 x 10 x 0.465 mm (Kymatech) using a 0.2 μm thick aluminum layer and measured (Agilent network analyzer, type 8753ET, Agilent Technologies Incorporation, Santa Clara, CA).

The measured amplitude responses of SAW and APMs are shown in Fig. 5. Just above the SAW passband (marker 1), a mixture of SAW sidelobes and low velocity APMs is the source of an about 33 dB higher insertion loss compared to SAW (markers 2 and 3). Above this area, the insertion loss difference first increases by about 60 dB, because of the very small values of K^2 (Fig. 2, $m = 10$), and next decreases to a value of about 4 dB, at an about two times higher frequency (marker 5). A characteristic property of this APM (Fig. 3b) is a strong concentration of the dominant longitudinal component u_1 of mechanical displacement at both planes of the GaN plate (Fig. 3b).

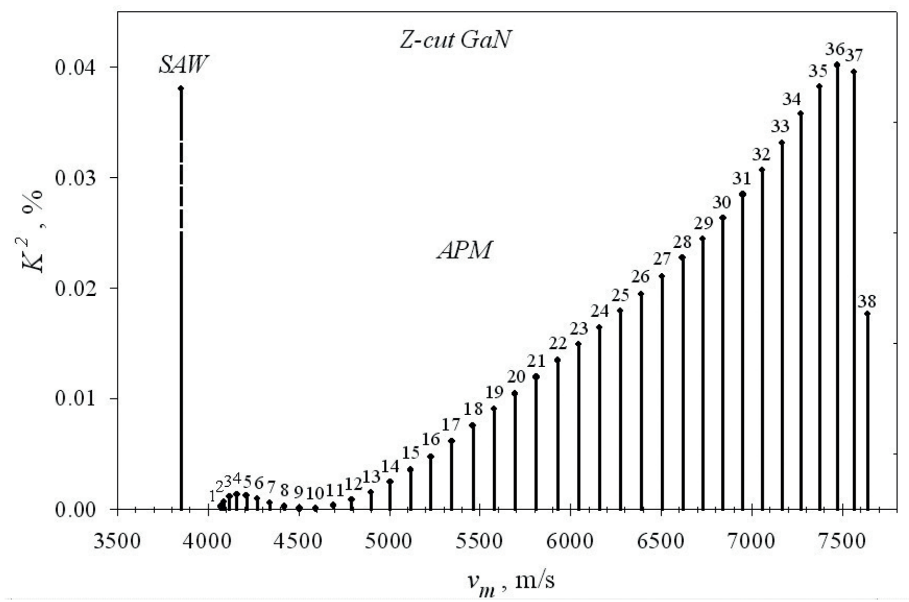
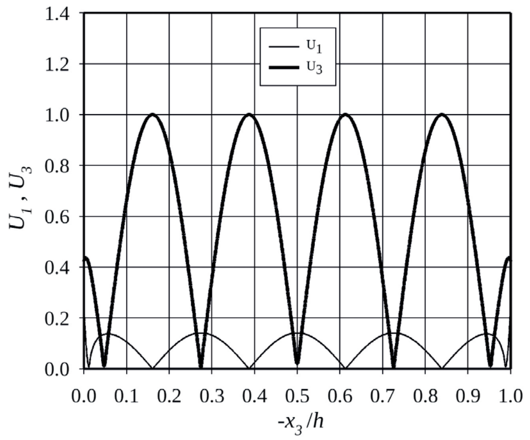
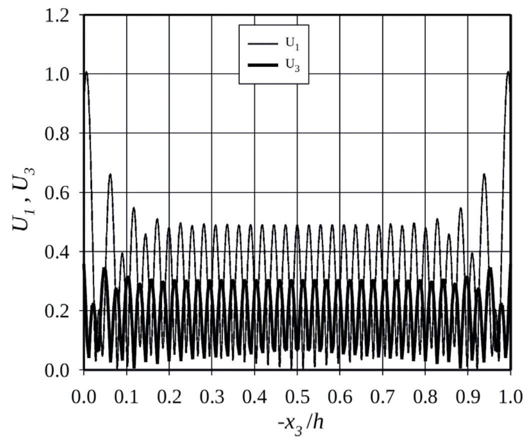


Fig. 2. Calculated electromechanical coupling coefficients of SAW and APMs as a function of velocity. For SAW K^2 = 0.25%. The m values = 1, 2.., 38 are mode identifiers. The area of small K^2 is limited by modes as follows: $1 < m < 10$. For $10 < m < 36$ the K^2 value is monotonically increased. The plate thickness to acoustic wavelength ratio h/λ is equal to 14.5.
Rys. 2. Obliczone współczynniki sprzężenia elektromechanicznego AFP i AMP w funkcji prędkości. Dla AFP K^2 = 0,25%. Liczby m = 1, 2.., 38 identyfikują mody. Obszar małego K^2 jest ograniczony modami $1 < m < 10$. Dla modów $10 < m < 36$ wartość K^2 monotonicznie rośnie. Stosunek grubości płytki do długości fali akustycznej h/λ przyjęto na poziomie 14,5.



(a)



(b)

Fig. 3. Distributions of longitudinal U_1 and vertical U_3 APM mechanical amplitude components inside the Z-cut GaN plate, where h is the plate thickness, (a) $m = 4$ and (b) $m = 36$.
Rys. 3. Rozkłady podłużnej U_1 i pionowej U_3 składowej amplitud mechanicznych AMP wewnątrz płytki GaN cięcia Z, h jest grubością płytki, (a) $m = 4$ i (b) $m = 36$.

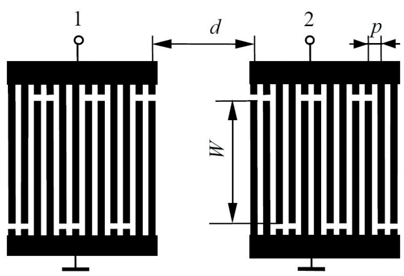


Fig. 4. The structure of a simple SAW filter; 1, 2 are the filter input and output interdigital transducers (IDTs), *p, W, d* are the period of electrodes, aperture and distance between IDTs, respectively.
Rys. 4. Struktura prostego filtru z AFP; 1 i 2 oznaczają wejściowy i wyjściowy przetwornik międzypalczasty (PM) filtru, *p, W, d* są odpowiednio okresem elektrod, aperturą, odległością między PM.

4. Conclusions

From the point of view of SAW filter properties, at the high frequency stopband, the mode free range (MFR) should be high. It was found that MFR is

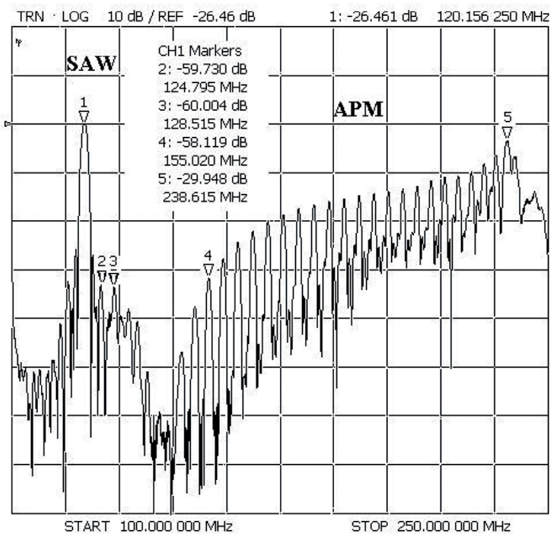


Fig. 5. The measured amplitude spectrum of SAW and APMs in the Z-cut GaN plate, for which the thickness to acoustic wavelength ratio $h/\lambda = 14.5$; $\lambda = 4p$, where p is the period of electrodes (see Fig. 4); marker 1 – SAW resonance, markers 2, 3 – mixture of SAW sidelobes and low velocity APMs, marker 4 – resonance of mode $m = 15$, marker 5 – resonance of mode $m = 36$.
Rys. 5. Zmierzone spektrum amplitudowe AFP i AMP w płytce GaN cięcia Z, w której stosunek grubości do długości fali akustycznej wynosi $h/\lambda = 14{,}5$; marker 1 – rezonans AFP, markery 2, 3 – superpozycja wstęg bocznych AFP i modów AMP o małej prędkości, marker 4 – rezonans modu $m = 15$, marker 5 – rezonans modu $m = 36$.

about 5.5% for GaN. It can be compared to about 1.7% for YZ $LiNbO_3$ and 4.5% for ST cut quartz [1]. A deep minimum of K_2 at $m = 10$, and low K_2 inside the first APM range (Fig. 2), make the GaN crystal attractive for application in SAW filters. The lowest insertion loss APM ($m = 36$) in GaN exists at an about two times higher frequency of SAW. This mode can be used in APM sensors, because the energy of the dominant longitudinal component of mechanical displacement is concentrated near both planes of the GaN plate.

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