Diamond & Related Materials 22 (2012) 66–69

Contents lists available at SciVerse ScienceDirect

Diamond & Related Materials

journal homepage: www.elsevier.com/locate/diamond

Theoretical study of Lamb acoustic waves characteristics in a AlN/diamond composite membranes for Super High Frequency range operating devices

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ARTICLE INFO

Article history:
Received 21 June 2011
Received in revised form 21 October 2011
Accepted 27 October 2011
Available online 22 December 2011

Keywords:
AlN/Diamond membrane
Lamb waves
SHF
SAW

ABSTRACT

In this work, zero order symmetrical Lamb waves mode (S_0) in AlN/diamond composite membranes is studied by means of a theoretical analysis. These composite membranes combine the advantages of film bulk acoustic waves and high velocity surface acoustic waves resonators in terms of acoustic isolation and electrodes micromachining technology respectively. Analysis of S_0 mode characteristics show that a bulk transducer with double side metallic topology gives the largest piezoelectric coupling coefficient K^2 up to 4.5% over a wide frequency range (up to 12 GHz). Additional results demonstrate that AlN/SiO_2/diamond membranes provide efficient temperature compensation of frequency when operating in a super high frequency range.

1. Introduction

Considering the rapid extension of Super High Frequency (SHF) wireless networks providing high speed and broadband service, the development of robust, compact, low cost and high-performance microwave devices based on electro-acoustic resonators attracts great attention. These components act generally as filters in both radio frequency and intermediate frequency sections of transceiver electronics. Among the variety of electro-acoustic devices, thin Film Bulk Acoustic Resonator (FBAR) and Solidity Mounted Resonator (SMR) concepts based on AlN films [1,2] operate at high frequencies determined both by the thickness of piezoelectric thin films and by the surrounding layers. Consequently, the operating frequency depends strongly on the layer thickness variation. Another family of electro-acoustic devices is based on High Velocity laterally excited Surface Acoustic Waves (HVSAW) modes. These devices are based on a piezoelectric thin film and a non-piezoelectric substrate. Several structures based on aluminium nitride were investigated such as AlN/Sapphire and AlN/diamond structures [3–5]. The latter is the most attractive for HVSAW devices as it can provide the highest acoustic waves velocity in the range of 5–10 km.s^{-1} and an electromechanical coupling coefficient K^2 up to 2.5% when optimal AlN thickness, wavelength (λ) value and electrical boundaries are well chosen and the most interesting modes are considered. Resonators and filters operating at 5 GHz with low insertion losses based on HVSAW propagating on AlN/diamond were demonstrated [5]. One of the major disadvantages of this last concept is the relatively high cost due to the fabrication difficulty regarding single-chip Radio Frequency (RF) module based on thicker diamond substrate with a large surface. From this point of view, thin film plate acoustic resonators using the S_0 zero-order symmetrical mode is a quite promising alternative. This concept has been recently achieved on AlN membranes. Furthermore, theoretical predictions were done on AlN/SiC membranes for high operating frequency and high quality factor, and also on ZnO/diamond membranes [6–9]. The lamb waves mode takes advantage from the waves confinement in the membrane due to the acoustic isolation obtained by the double side air-boundary. Furthermore, such devices are able to adjust the resonance frequency by the Inter-Digital Transducers (IDTs) design and the membrane thickness. These devices operating with the Lamb S_0 mode combine the advantages of FBAR/SMR acoustic isolation, operation frequency in GHz range, and HVSAW electrodes micromachining technology.

During the last decade, the low temperature growth of uniform, polycrystalline and Ultra/Nano-Crystalline Diamond (U/NCD) thin films was developed. Their mechanical properties are close to those of the single crystal diamond [10–13]. These films are obtained either by microwave plasma or hot filament chemical vapour deposition processes. Mechanical and electrical properties make the Poly/Nano-Diamond (PD,ND) thin films attractive candidates for high-performance Micro/Nano Electro-Mechanical Systems. These thin films have been used for the fabrication of RF switches, mechanical resonators and actuators [11,14–16]. Nowadays, the ability to grow uniform diamond thin films over a large area (>2" wafer) at low temperature permits the integration of diamond devices with Complementary Metal-Oxide-Semiconductor (CMOS) electronics. These devices are also compatible with a technology based on wide band gap materials (AlN,GaN) [17–20].

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0925-9635/$ – see front matter.
doi:10.1016/j.diamond.2011.10.027

In this work, a theoretical analysis of AlN/diamond composite membranes for S_0 acoustic wave-guides is reported. This exhibits excellent acoustic waves properties making these devices an alternative to HVSAW on AlN/diamond substrate for SHF resonators. Other applications can be envisaged using this structure, such as acoustic waves devices sensors in harsh environment, or reliable micro/nano structure for phononic crystal slab waveguides.

2. Design considerations and analysis method

The AlN/diamond membrane is optimized in order to achieve S_0 mode with operation frequency range varying from 1 GHz to 12 GHz, and taking into account the AlN and diamond thin films standard micromachining constraints. At present, as deposited thick diamond films exhibit high surface roughness, not suitable for micrometer or sub-micrometer resolution processes. From this point of view the thickness of diamond is between 0.5 and 1 μm in order to address the problems related to the rigidity and surface roughness. Additionally, to take the advantage of the high velocity acoustic waves in diamond, the AlN thin films thickness does not excess more than 2 times the diamond thickness. Consequently, in this study the total thickness of AlN/diamond composite membranes is chosen between 1 and 2 μm.

The optimal structure of the composite membrane is defined in order to achieve maximum K^2 coefficient at SHF frequency range and zero Temperature Frequency Coefficient (TCF). Therefore, we have studied the effect of different electrical interface boundaries, wavelengths and membrane layers thickness on the S_0 mode operating frequency and K^2 coefficient. Also, we have investigated the intrinsic thermal compensation of AlN/diamond Lamb structures using silicon dioxide layer.

Operating frequency F and K^2 coefficient of AlN/diamond composite membranes are calculated following the similar approach developed by Campbell and Jones for surface acoustic waves and extended in this study to lamb waves [21]. The matrix method is used here to calculate the phase velocity in the layered piezoelectric membranes, using motion and Poisson's equations. The boundary conditions require that the acoustic displacements and stresses be continuous at the AlN-diamond interface and the stress-free surface is assumed on both sides of the membrane. In addition, the electric potential and the normal component of electric displacement must be continuous at the interface for an electrically free surface. For a metalized (thin metal film) surface, the electric potential is equal to zero. The material constants and their temperature dependence used in the model correspond to the bulk values of AlN, diamond and silicon dioxide. The computing method consists to find numerically the phase velocity (v_p) by means of minimum solution of the boundary conditions determinant for a given wavenumber (λ^{-1}) and a composite membranes layers thicknesses. The operating frequency F is then calculated using the following relation $F = v_p \times \lambda^{-1}$. The electromechanical coupling coefficient estimation is based on phase velocities difference defined as:

$$K^2 = \left(v_0{}^2 - v_m{}^2\right) / v_0{}^2$$

where v_0 indicates the phase velocity when the membrane surface is electrically opened (free surface), while v_m shows the phase velocity when the membrane surface is electrically shorted (metallized surface). For Lamb waves, this method gives similar results to that of the Green's function method, as reported for ZnO/diamond membranes [9] and AlN membranes [7].

Fig. 1 illustrates the four transducers/electrodes topologies used in this work to study the performance of S_0 mode in AlN/diamond composite membranes.

3. Theoretical results and discussion

3.1. Electromechanical coupling coefficient and frequency dispersions curves of AlN/diamond membranes

S_0 mode propagation characteristics are calculated for each AlN/diamond membrane topology. Wavelength λ is chosen in the 1.6-10 μm range to model devices operating in the SHF frequency domain. AlN/diamond membranes with a constant thickness (i.e. 1.5 μm) are considered, to evaluate the effect of the diamond thin film contribution onto S_0 mode propagation characteristics. Theoretical operating frequency and K^2 coefficient versus the wavenumber are shown in Figs. 2–3 for all the structures.

This study shows that for a given membrane thickness, the K^2 coefficient presents a maximum value for a specified wavenumber and an AlN/diamond thickness ratio. When the thickness of the diamond layer increases, the maximum value of K^2 is shifted to larger wavenumbers. Due to its mechanical properties the diamond layer permit to improve the rigidity of the membrane which in turn permits to increase the operation frequency as shown Fig. 3.

Configurations type A3 (with a metallic layer on the top of AlN and IDTs at the interface between AlN and diamond layer) and A4 (IDTs at the AlN surface and AlN/diamond interface) exhibit a higher K^2 coefficient reaching 3.35% and 4.5% respectively. This is explained by the IDTs position in the structure which influences the electrical field distribution in the AlN thin films. The favorable situation for the case of S_0 mode generation is an homogeneous distribution of the electrical field lines along the AlN thickness direction. The topology A4 is the well adapted to fulfill this requirement because the electrical field components are purely along the AlN thickness direction. The A3 topology permits again an improvement of the electrical field distribution along the AlN thickness due to the IDTs position at the interface

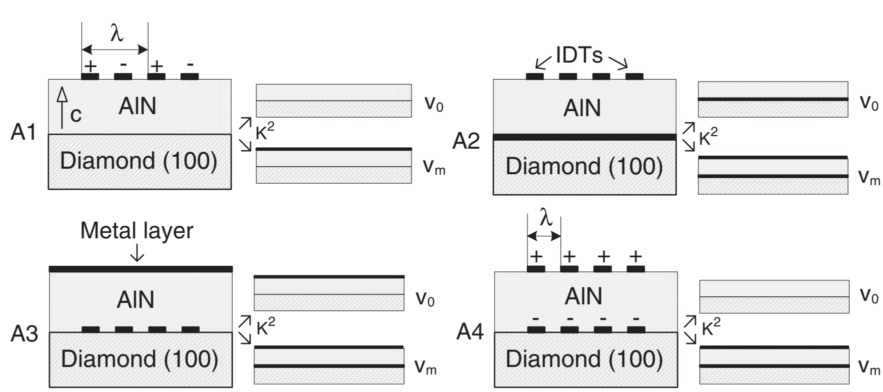

Fig. 1. Lamb waves devices Schematic representation in AlN/diamond composite membranes with various transducers/electrodes topologies: (A1) IDTs/AlN/diamond, (A2) IDTs/AlN/Metal/diamond, (A3) Metal/AlN/IDTs/diamond and (A4) IDTs/AlN/IDTs/diamond.