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Theoretical investigation of Lamb wave A_0 mode in thin SiC/AlN membranes for sensing application in liquid media

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ABSTRACT

The propagation of the fundamental Lamb antisymmetric A_0 mode along amorphous-SiC/*c*-AlN and 3C-SiC/*c*-AlN thin composite plates is investigated with respect to the AlN and SiC layers thickness, propagation direction and electrical boundary conditions. The A_0 mode phase velocity and the electromechanical coupling coefficient (K^2) dispersion curves were theoretically studied for four different electroacoustic coupling configurations. For each configuration the highest K^2 values (from 1 to 2%) were found corresponding to A_0 mode phase velocity lower than the liquid medium compressional velocity (1480 m/s). The gravimetric sensitivity of these configurations was then calculated, specifically addressing the design of enhanced-coupling mass sensors able to work in liquid ambient. The performances of the A_0 mode AlN/SiC plates were compared with those of the enhanced coupling ($K^2 = 4\%$) ZnO/SiN plates for liquid sensing applications: the former higher operation frequencies and remarkable endurance to high temperature and chemical etching, make it the ideal candidate for the development of elettroacoustic devices able to survive to harsh environment.

1. Introduction

The electroacoustic devices based on the surface and bulk acoustic waves (SAW and BAW) propagation, such as resonators or delay lines, are known for their wide range of applications in chemical, biological and physical sensing fields. When these devices are required to operate in liquid environment for either biotechnological or biomedical analysis, they must involve the propagation of specific types of acoustic waves that do not radiate energy into the liquid. The types of acoustic waves that are suitable as the sensing elements in liquid environments include Love waves, surface skimming bulk waves, surface transverse waves or acoustic plate modes: their shear horizontal polarization ensures no coupling between the liquid and the elastic propagating medium [1]. Waves with large shear vertical and longitudinal particle displacement amplitude (such as the Rayleigh waves) are impractical for use in liquid environments as a consequence of the high energy loss in the liquid. The fundamental antisymmetric A_0 Lamb mode, while being elliptically polarized, can travel along thin membranes that are in contact with a liquid as a consequence of its dispersive phase velocity that can be designed to be lower than the liquid medium compressional velocity, at the proper plate thickness. The membrane acts as a waveguide where the ultrasonic wave energy is confined rather than dispersing into the surrounding medium, and only the evanescent wave penetrates the fluid. In recent years AlN piezoelectric thin films have been used to fabricate a wide variety of radio frequency resonators and filters for applications to telecommunication and sensing fields, thanks to its several remarkable characteristics [2]. AlN is the fastest piezoelectric materials among those that can be grown in thin film form: compared to ZnO, for example, AlN films show higher surface acoustic wave (SAW) velocity (5607 m/s as opposed to 2682 m/s), higher hardness (17.7 GPa as opposed to 4.7 GPa), and thermal conductivity (2.8 W cm^{-1} °C^{-1} as opposed to 0.6 W cm^{-1} °C^{-1}) and slightly lower electromechanical coupling coefficient K^2 (0.3% as opposed to 0.97%). The AlN resistance to high temperature and to caustic chemicals make it the ideal candidate for the development of elettroacoustic devices able to survive to harsh environment.

Cubic polytype of SiC (3C-SiC) substrates have been proved to be suitable for the implementation of AlN-based multilayered devices thanks to some interesting properties such as low mechanical loss, high SAW phase velocity, resistance to chemicals, high hardness, low lattice mismatch (1%) and thermal expansion coefficient that closely matches that of AlN. Large-area low-cost 3C-SiC(1 0 0) and (1 1 1) *films* on Si(1 0 0) and (1 1 1) substrates are commercially available [3,4] for limited thickness ranges (respectively up to 1 and 20 μm thick), while amorphous SiC films can easily be deposited on Si substrates by rf sputtering technique [5]. Highly *c*-axis oriented AlN *films* have been grown on 3C-SiC *films* by reactive magnetron sputtering [5,6] and the propagation of the first symmetric mode S_0

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has been theoretically predicted [7] and experimentally observed [8] along thin 3C-SiC/AlN suspended membranes. Recently, the A_0 mode propagation along ZnO/SiN thin membranes has been investigated for sensing applications [9], and a K^2 (4%) two times that of AlN/SiC membranes has been estimated at a phase velocity (~372 m/s) half that of AlN/SiC plate. The low ZnO/SiN phase velocity (and hence the operating frequency) can be increased by increasing the ZnO normalized thicknesses, but at the price of lowering the K^2 by a great amount, as a consequence of the sharp behavior of the K^2 dispersion curve. Thus comparable K^2 and phase velocity values can be obtained for A_0 mode propagating along the ZnO/SiN and AlN/SiC plates at the same frequency, but the better thermal and mechanical properties of the latter plate make it preferable to the former.

In the present paper the A_0 mode propagation along amorphous-SiC/c-AlN and 3C-SiC/c-AlN composite plates is theoretically investigated, specifically addressing the design of enhanced coupling, microwave devices for liquid sensing application. A Lamb waves device consists of an acoustically thin membrane that is typically fabricated by bulk micromachining of a specifically orientated Si wafer. In addition to the Si substrate, a silicon carbide (SiC) thin film is used as an etch stop and to form the underlying membrane of the device. A piezoelectric aluminum nitride (AlN) film is deposited on the SiC layer, followed by a metallic layer (typically Al, Mo or Pt) on which the interdigital transducers (IDTs) are photolithographically patterned to generate and detect the propagating acoustic waves. The fabrication procedure of the SiC/AlN-based Lamb wave sensors is compatible with the semiconductor processing techniques, thus offering the advantage of providing the monolithical integration of the sensor with the signal processing electronics.

2. Theoretical analysis

2.1. SiC/AlN dispersion curves

Fig. 1 shows the dispersion curves of the fundamental *symmetric* S_0 and *antisymmetric* A_0 modes propagating along the SiC(001)⟨100⟩/c-AlN composite plate, being 0.1 the SiC thickness-to-wavelength ratio h/λ_{SiC}. With increasing the AlN normalized thickness, h/λ_{AlN}, the velocity of the two modes asymptotically reaches the velocity of the SAW in the plate. The A_0 mode is clearly identified by its reducing velocity as the plate thickness approaches zero. In a liquid environment, the acoustic wave phase velocity must be lower than the compressional velocity of the fluid to confine the acoustic energy to the propagating structure rather than dissipating it into the surrounding liquid medium. The compressional velocity of water is $v_l = 1480$ m/s. Another benefit of the low-velocity A_0 mode is that it allows for inexpensive signal processing equipment to be used, due to its low resonant frequency $f = v/\lambda$. The phase velocity dispersion curves of the A_0 mode propagating along the a-SiC/c-AlN, SiC(001)⟨100⟩/c-AlN and SiC(001)⟨110⟩/c-AlN composite plates were calculated for different SiC normalized thicknesses. The calculations were performed exploiting the numerical code developed by Adler and coworkers at McGill University, Montreal, Canada. A detailed description of the propagation of surface and plate acoustic waves in layered structures can be found in Farnell and Adler's work [10–12], which originates from Campbell and Jones method [13]. The calculations were performed under the hypothesis of lossless materials, and assuming the single crystal AlN and 3C-SiC material constants available in the literature [14,15]. The SiC/AlN composite plate was considered to be an infinite plate in the *x* and *z* directions, being *x* the propagation direction.

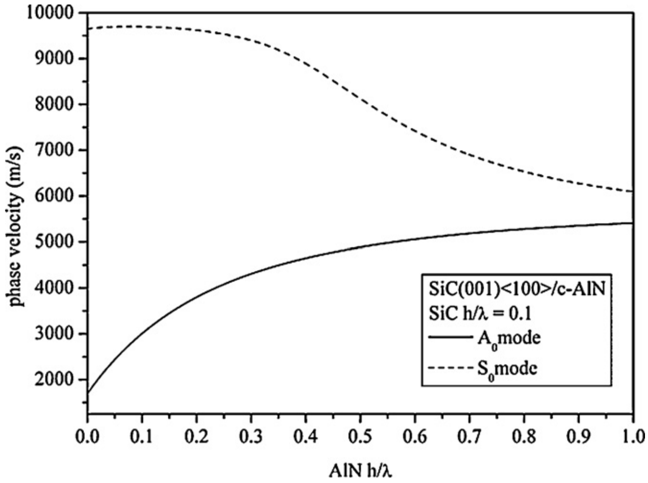

Fig. 1. The phase velocity of the S_0 and A_0 modes propagating along SiC(001)⟨100⟩/AlN vs the AlN normalized thickness, for SiC normalized thickness equal to 0.1.

2.2. SiC/AlN electroacoustic coupling dispersion curves

The electroacoustic coupling coefficient, K^2, is a parameter of primary importance for the design of acoustic waves devices since only K^2 of the total input of the electrical energy is converted to elastic energy. For layered structures, the achievable K^2 value is frequency dispersive and depends on the type and orientation of the piezoelectric material, and it is drastically affected by the location of the IDTs and ground electrode with respect to the AlN layer. An A_0 mode device able to work in liquid media must show a phase velocity v^u lower than that of the liquid $v^{water} = 1480$ m/s at maximum electroacoustic coupling. A good K^2 value ensures that sufficient electrical energy is converted to mechanical energy and vice versa, and $v^{ll} < v^{water}$ ensures that the A_0 Lamb mode energy is confined rather than dispersing into the liquid medium. In the AlN/SiC composite plate, four piezoelectric coupling configurations can be obtained by placing the interdigital transducers (IDT's) at the substrate/film interface (substrate/transducer/film, STF), at the film surface (substrate/film/transducer, SFT), farther including a ground electrode opposite the IDTs (substrate/transducer/film/metal and substrate/metal/film/transducer, STFM and SMFT), as shown in Fig. 2. The K^2 can be obtained by calculating the perturbation of the phase velocity when the tangential electric field component is shorted out at the AlN surface: for each configuration it can be

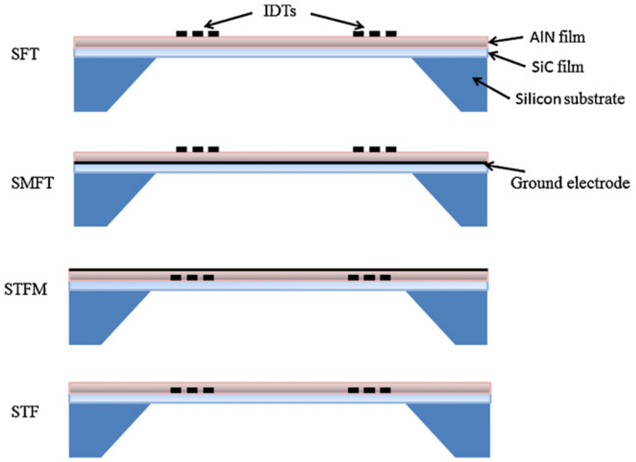

Fig. 2. The cross section of the four coupling configurations: SFT, SMFT, STF and STFM.