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Packageless temperature sensor based on AlN/IDT/ZnO/Silicon layered structure

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Abstract— The possibility to generate simultaneously Surface Acoustic Wave (SAW) and Waveguiding layer acoustic wave (WLAW) in layered structures AlN/ZnO/Silicon was investigated. A delay line operating at 525 MHz was tested versus temperature in air and in contact with liquid. Experimental characterizations were also supported by modeling using the commercial software (COMSOL Multiphysics). The full delay line was simulated and liquid modeled by an additional layer on the top of AlN film.

Keywords- AlN; packageless; silicon; temperature sensor; ZnO

I. INTRODUCTION

Devices based on wave guiding layer acoustic waves (WLAW) present a great interest in sensor application due to packageless structure, the possibility of extreme miniaturization and reduced sensibility to chemical environment. To generate isolated waves, the structures combining layers with low and high impedance in Bragg mirror configuration (ILAW-Isolated Layer Acoustic Wave) or acoustic confinement of the wave in a low-acoustic-velocity layer between two high-acoustic-velocity materials were used [1]. There are several requirements for the guiding layer: to be highly oriented and to have low surface roughness to ensure a good wave transmission and to avoid the increase of the acoustic propagation losses [2-4]. The isolated layer can be dielectric, piezoelectric or metallic and has to be stress- and crack-free and relatively thick for the confinement of the wave. Electro-acoustic properties of isolated wave, such as propagation velocity and electromechanical coupling are highly dependent on the nature, thickness and geometrical configuration of the materials composing WLAW device. To this date, few studies have been reported in the literature on this type of structure [1, 5-7]. The successful confinement of WLAW in structures based on SiO₂ guiding layer was reported by Zhgoon et al. [1, 7]. However, more efforts need to be done to increase the coupling coefficient of such structures. Due to its low acoustic velocity and its high electromechanical coupling, zinc oxide was one of most promising material for the guiding layer. Our previous works have shown theoretically and experimentally, the possibility to generate Waveguiding

layer acoustic wave in layered structures AlN/ZnO/diamond [8]. Such structures are of great interest because of their potential applications as packageless resonators, filters or sensors, based on WLAW, and as thermally compensated gas or liquid sensors, based on the combination of both SAW and WLAW. Because of its high acoustic velocity, the diamond appears to be the most suitable substrate for the production of containment structures for WLAW wave type, but it has major drawbacks including its high price and its poor compatibility with CMOS technology. In addition, the diamond growth occurs at high temperatures (700 °C - 1000 °C) inducing significant stress in the heterostructure. Therefore heterostructures with diamond are unsuitable for mass production.

The aim of this work is to evidence the potential of the AlN/ZnO/Silicon structure as low cost, CMOS compatible and packageless temperature sensor able to operate in harsh environments. Theoretical investigation was realized by using a finite element method (FEM) in order to define the best configuration and the optimized thicknesses of different layers. To achieve efficient confinement of WLAW, AlN layer was deposited on operating SAW device (IDT/ZnO/Si). The frequency response and thickness of AlN were monitored in real-time and during AlN film deposition. The second part of this paper is devoted to the experimental realization of the heterostructure with a comparison of results obtained by the simulation.

II. THEORETICAL DETAILS

Theoretical investigation was realized by a finite element method (FEM) using COMSOL Multiphysics [9]. The full delay line was simulated and liquid was modeled by an additional layer on the top of the AlN film.

$kh_{\text{ZnO}} = 1.25$ has been chosen i.e. ($\lambda = 10 \mu\text{m}$, thickness (ZnO) = $2 \mu\text{m}$, thickness (AlN) $> 20 \mu\text{m}$).

The materials are described by their physical constants (elastic, piezoelectric, dielectric...), reported in literature [10-12].

The confinement of the wave was demonstrated by analyzing the field distribution of the wave in the structure notably the acoustic wave displacement profile.

III. EXPERIMENTAL SETUP

2 μm thick ZnO films were deposited on Si (100) by rf magnetron sputtering. The pressure in the chamber was 0.002 mbar (1:1 of Ar: O₂) and the power injected in the plasma was 100 W. The distance target-substrate was fixed at 80 mm and the substrate temperature was 450°C. Then IDT were fabricated on ZnO/Si surface by using Aluminum sputtering followed by photolithography and wet etching processes. The number of IDT fingers, the aperture width (W) and the gap were set to 40, 0.4 mm and 200 μm , respectively. Finally, 30 μm of AlN were deposited on IDT/ZnO/Si by rf magnetron sputtering. AlN deposition process was optimized to avoid the AlN film cracking even in the case of thick layer. Following our experience, the key consists in working at relatively low deposition temperature (343 K). To perform electrical characterization, vacuum tight rf connectors were installed in the magnetron vacuum chamber. During AlN layer deposition, in-situ measurements of frequency and insertion losses of different modes were performed by a network analyzer (Agilent N5230A) and AlN thickness was monitored by interferential reflectometry method.

IV. RESULTS AND DISCUSSION

1D-curves and 2D representation of modeling results for the particles displacement in AlN/ZnO/Si hétérostructure obtained for 2 μm and 12 μm of AlN thickness are shown in Fig.1 (a) and (b). The AlN thickness influences the confinement of the wave. Indeed, one can clearly observe that with 2 μm of AlN, the displacement of particles was reduced at the surface that corresponds to 30 % of confinement, at 12 μm of AlN zero displacement of particle was observed resulting in a total confinement of the wave. The addition of liquid on top of the AlN film in modeling induces no serious change in transmission signal that proves theoretically the confinement of the wave (Fig. 1(c)). The evolution of frequency response in transmission mode (S_{21}), obtained experimentally, related to the 0th, 1st and 2nd mode of acoustic wave, with AlN layer thickness is shown in Fig. 4. Before AlN deposition, only the 1st mode was observed due to the low electromechanical coupling of the other mode. At 12 μm of AlN thickness, the mode 1 starts to confine and the surface acoustic wave of 2nd mode appears. Frequency-Temperature characteristic shows a

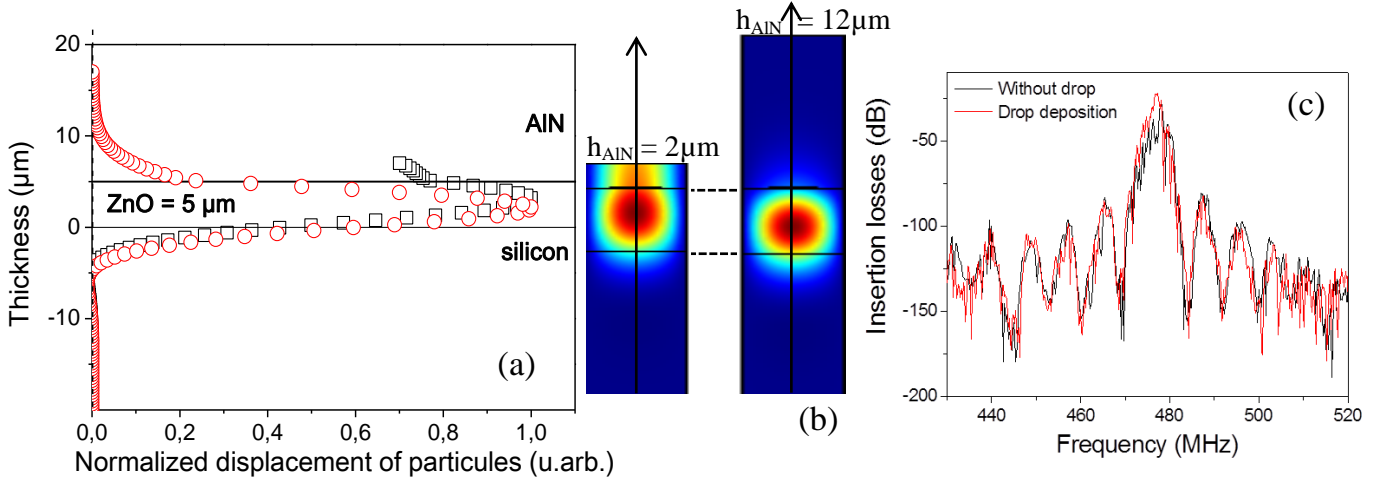


Fig.1: (a) 1D-curves and (b) 2D representation of modeling of the displacement of particles in AlN/ZnO/Si heterostructure obtained for 2 μm and 12 μm of AlN thickness. (c) Transmission signal of a delay-line obtained by modeling in air and with water over-layer.

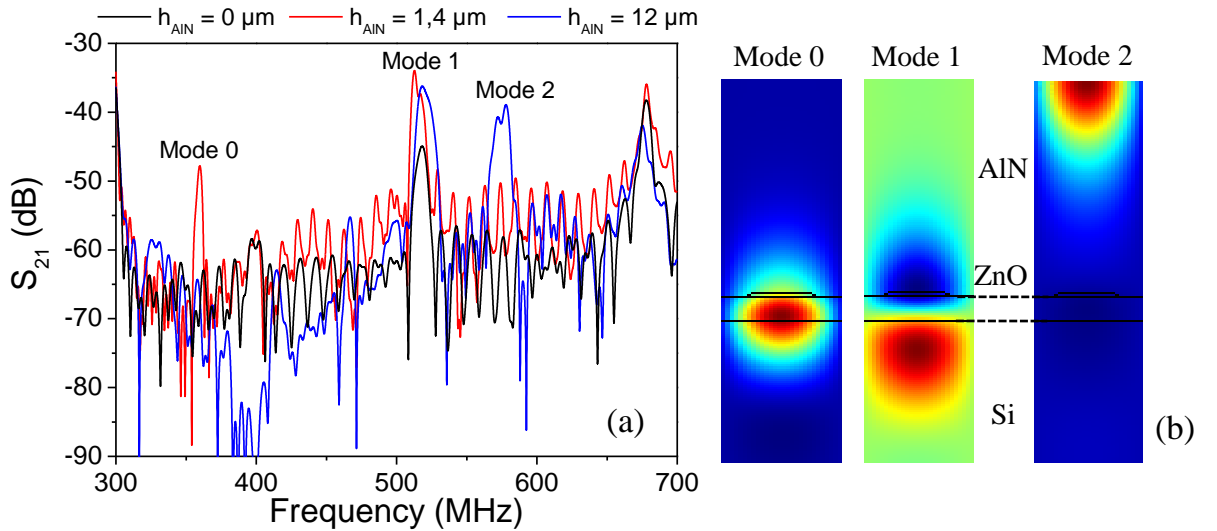


Fig. 2: (a) SAW signal (S_{21}) before and after deposition of AlN with the thickness of 1.4 and 12 μm for the heterostructure AlN / ZnO / Si where $kh_{\text{ZnO}} = 1.25$. (b) 2D representation of modeling results for particle displacement in AlN/ZnO/Si hétérostructure obtained for 12 μm of AlN thickness for the mode 0, 1 and 2.

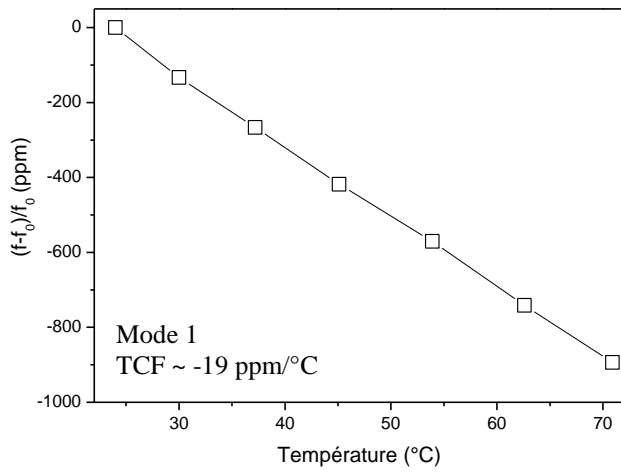


Fig 3: Relative velocity variation with temperature of AlN/ZnO/Si structure.

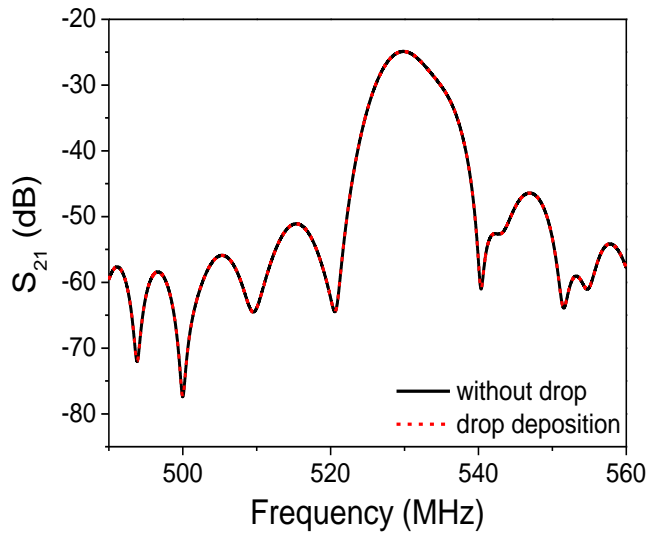


Fig. 4: Experimental test of the wave's confinement with addition of a water micro drop on the gap between the IDTs of the device.

very good linearity and a TCF value of $-19 \text{ ppm/}^\circ\text{C}$ in air and in contact with liquid (Fig. 3). One can also observe that there is no change in transmission responses (S_{21}) collected in both conditions (Fig. 4). These results prove the total confinement of the wave in the AlN/IDT/ZnO/Si structure. Note that a Rayleigh wave on open surface is partially or completely attenuated. This study confirmed the feasibility of the AlN/IDT/ ZnO/Si structure as a packageless sensor sensitive to temperature with the ability to protect itself.

V. CONCLUSION

The ability to generate in the same heterostructure three propagation modes 0, 1 and 2 of the acoustic wave, the confinement of the wave in the structure and good compatibility of the results obtained in simulation to experiment have been demonstrated. The characterization of the temperature behavior of the optimized heterostructure ($kh_{\text{ZnO}} = 1.25$), showed its potential as a temperature sensor. The measured TCF value is $-19.1 \text{ ppm/}^\circ\text{C}$. Finally the effective acoustic isolation of the wave within the heterostructure AlN / IDT / ZnO / Si has been demonstrated experimentally. Thus, this study allowed us to confirm the potential of the heterostructure AlN/IDT/ZnO/Si as the temperature sensitive device, having the ability to protect itself from air and moisture.

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