Isolated acoustic wave based on AlN/ZnO/diamond structure for sensor applications

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***Abstract*— We present a theoretical calculation and experimental results for an isolated acoustic wave. The experimental device is modeled by finite element method (FEM) for the structure AlN/ZnO/diamond. The phase velocity in the AlN/ZnO/diamond structure was investigated by theoretical calculations. It was found that the AlN thickness must be at least more than 3λ/2 to obtain a negligible surface displacement. In the same way the ZnO thickness for a fixed value of AlN at 2λ must be higher than λ/4 to confine the acoustic wave. The coupling of the wave presents an optimum around λ/2 for the ZnO layer thichness.**

Keywords-Isolated acoustic wave, Finite element modeling

I. INTRODUCTION

Several works are related to the propagation on interfacial wave between two layers [1-5]. In that case it avoids the wave interaction with the surface. SAW devices are sensitive to surface modification such as humidity or oxidation. Consequently, they must be encapsulated to protect them against the environmental influence. In the sensor applications we can use both the surface wave and the isolated wave, the first one is very sensitive to the effect on the surface and to temperature or pressure while the isolated wave is only sensitive to pressure or temperature. The principle of Isolated Layer Acoustic Wave (ILAW) is based on an acoustic confinement of the wave in a low acoustic velocity layer between two high acoustic velocity layers. The isolated acoustic wave propagates inside the low acoustic velocity that is placed between two layers of high acoustic velocity material. Such package-less possible structure have been recently studied [6-8]. In our case we used a ZnO internal layer, and the most reliable acoustical isolation could be obtained with diamond/ZnO/diamond structure. But the diamond growth is carried out at high temperature that destroys the transducer deposited under ZnO. In this concept, the interdigital transducer must be in contact with a piezoelectric film (Fig.1). Consequently several materials configurations (Piezoelectric, dielectric or metallic) are possible in order to generate an isolated acoustic wave. Of course the electromechanical coupling coefficient and the propagation velocity strongly depend on the configuration choice. In our case the propagation of the wave inside the relatively low acoustic velocity wave guiding layer of ZnO is confined by the highest velocity substrate (Diamond) and by the topmost layer made with high acoustic velocity piezoelectric material (AlN) thus ensuring the creation of wave guiding by the ZnO. Our final configuration is formed by a dielectric (diamond) and two piezoelectric layers (ZnO and AlN). Many other configurations are also possible but this one seems to combine all the best properties of high velocity material and high piezoelectric coupling.

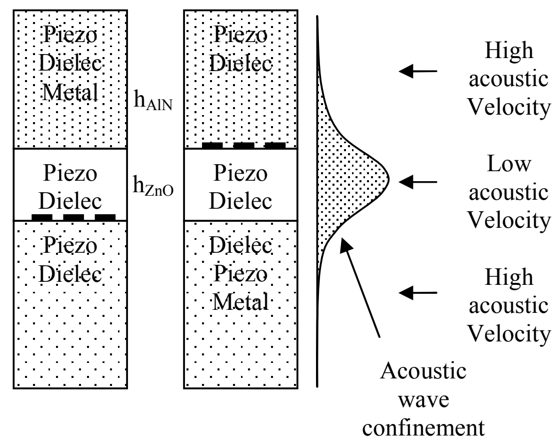


Figure 1. Isolated Wave principle

In this work we present the theoretical finite element method study of the acoustic wave in the previous layered structure.

II. RESULTS

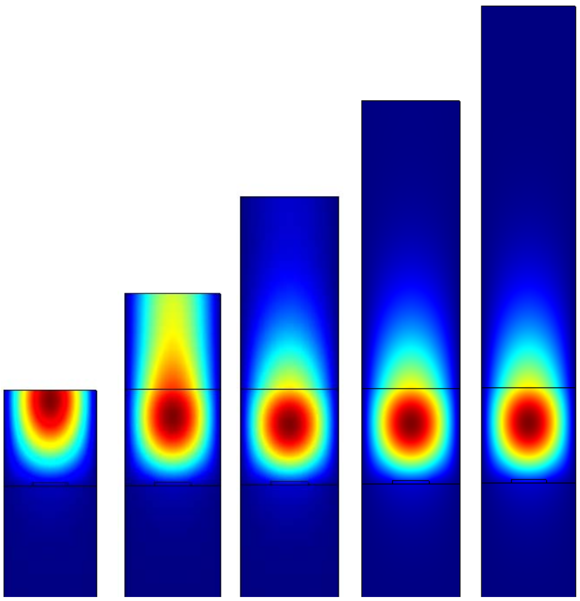
A. AlN thickness parameter

The AlN thickness parameter is one key parameter to obtain the acoustic isolated wave. At this step we must define the limit which corresponds to an ILAW. A reasonable way to attribute a limit is to decide that the surface displacement must less than 0.1 % of the maximum displacement in the structure.

The figure 2 Shows the Y AlN deformation shape for the first mode. The ZnO thicknes (h_{ZnO}) was fixed at 4 µm and the wavelength (λ) at 8 µm. The AlN thickness increases from 0 (Fig. 2-a) to 16 µm (Fig. 2-e), which correspond to 2λ. The figure 2 (a) shows the deformation shape of the surface acoustic wave for the ZnO/diamond conventional structure. The figure 2 (b) shows the effect of 4 µm of AlN at the top surface of the ZnO.

The acoustic wave Y deformation expands in the AlN film and decreases slowly but still important at the surface. For the figure 2

(c) the AlN thickness is equal to one wavelength and the acoustic wave is now confined between the diamond and the AlN materials and the surface amplitude represents 7 % of the maximum Y deformation in the layered structure. The figures 2 (d) and (e) show that the Y deformation shape does not vary and the acoustic wave is totally isolated between the AlN layer and the diamond. The normalized surface amplitude represents 1% for the (d) and 0.04 % for the (e) structure.



(a) 0µm (b) 4µm (c) 8 µm (d) 12 µm (e) 16 µm

Figure 2. Y deformation shape as a function of the AlN Thickness

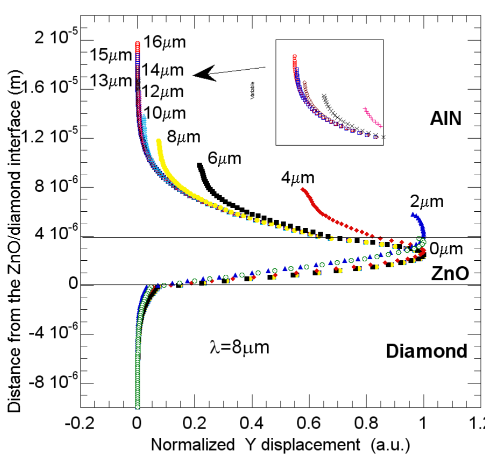


Figure 3. Y direction normalized displacement values for différents AlN tickness

The figure 3 shows the normalized Y displacement for the Diamond/ZnO/AlN structure. Those data are useful to determine the wave confinement and the minimum required AlN thickness. One can observe that the surface amplitude decreases rapidly as a function of the AlN thickness. With an AlN top film of 10 µm, the AlN surface displacement is only about 2 % of the maximum displacement in the structure. If we define a limit for an isolated wave at 0.1 %, we deduce from these results a required AlN thickness of 13.2 µm.

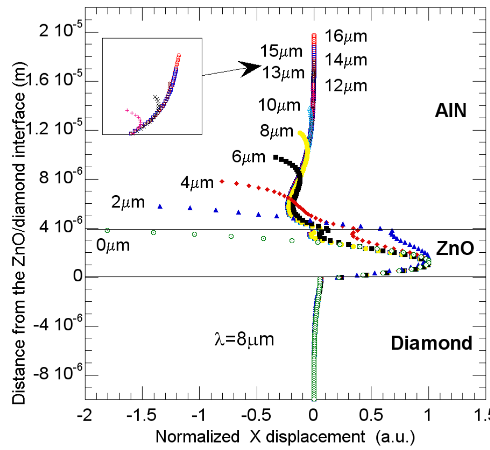


Figure 4. X direction normalized displacement values for different AlN thickness

The figure 4 shows the normalized X displacement for the Diamond/ZnO/AlN structure. We can also observe that the X surface amplitude decreases rapidly when the AlN thickness increase. The shape is different from the Y displacement but we found exactly the same results for the wave confinement. With an AlN top film of 10 µm the AlN surface displacement is only about 2 % of the maximum displacement in the structure. If we define a limit for an isolated wave at 0.1 %, we deduce from these results a required AlN thickness of 13.2 µm.

In the diamond layer the elastic wave penetration depth is only 5 µm for 0.1 % of the maximum normalized amplitude. It is clear that due to its highest velocity, diamond is the ideal layer for an optimum confinement of the wave in the ZnO film.

The figure 5 shows the resonance frequency and the coupling as a function of the AlN thickness. As expected, the frequency increases with AlN layer thickness. Indeed, due to the higher velocity of AlN compared to ZnO one. The velocity starts at 2940 m/s without AlN layer and reach a relative saturation value of 4266 m/s from 6 µm of AlN thickness. No change of frequency is observed after 12 µm of AlN. The constant value of 533 MHz demonstrates the negligible effect of the AlN layer after a AlN thickness of 12 µm to a AlN thickness of 16 µm. Concerning the electromechanical coupling coefficient, the higher value is obtained without AlN. This value decreases with the AlN thickness, shows a minimum at 4 µm of AlN (λ/2), increases and reach a constant value of 5.6 % above 12 µm of AlN.

From the figure 2-5 we can conclude that the minimum AlN thickness for this structure is 3λ/2 and the penetration depth in diamond layer does not exceed 5 µm (about 2λ/3). When these two conditions are respected, the acoustic wave is fully confined and device frequency is not affected by the AlN upper film.

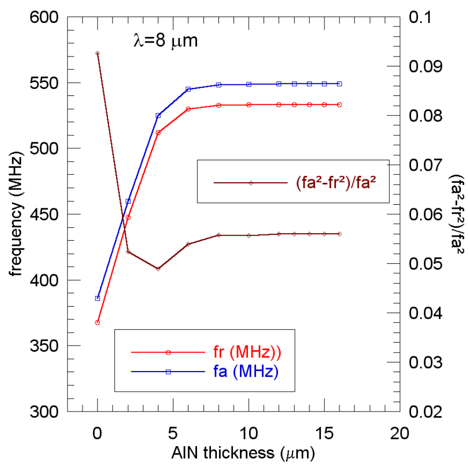


Figure 5. Device resonance fequency (fr) and antiresonance frequency (fa) as a function of the AlN thickness and electromechanical coupling obtain by the with $(fa^2-fr^2)/fa^2$ formula.

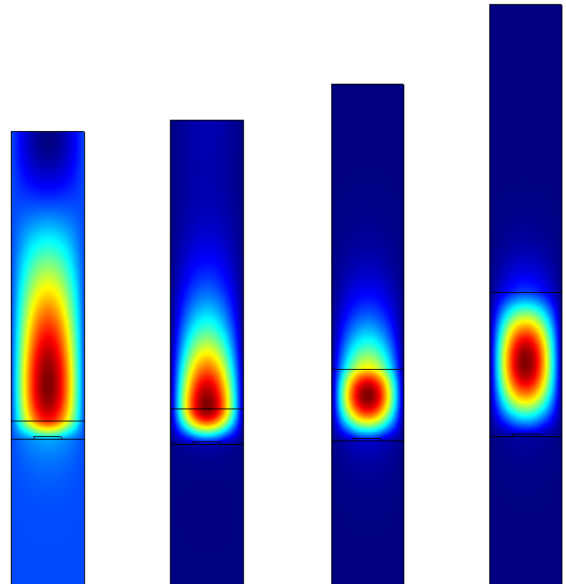


Figure 6. Y deformation shape as a function of the ZnO Thickness

B. *ZnO thickness parameter*

The ZnO thickness is also an essential parameter for the studied structure. The ZnO main role is to guide the acoustic wave, consequently for a finite structure formed by two parameters, h_{AlN} and h_{ZnO} the ZnO thickness could worsen the wave confinement for a fixed AlN thickness. We choose to fix an AlN thickness of 16 µm which correspond to 2λ and which shows a good confinement in the previous case. The ZnO thickness was varied from 1 µm to 8 µm. The figure 6 shows the Y deformation shape for ZnO layers of 1 µm to 8 µm thick. As can be seen on this figure the 1µm thick ZnO does not allow the wave confinement to be sufficient for a 16 µm thick AlN layer. The wave confinement starts to appear for that structure only after 2 µm of ZnO and the maximum of displacement is near the ZnO-AlN interface. At 4 µm of ZnO the main part of the wave is confined in the ZnO layer and the structure shows a well guided mode by the ZnO layer. For a ZnO thickness of 8 µm the acoustic wave is totally confined in the ZnO layer which corresponds exactly to one wavelength.

The figure 7 shows the admittance absolute value as a function of the frequency for different ZnO thicknesses. For the 1 µm of ZnO in the frequency range the admittance exhibits one peak at 756 MHz (v=6053m/s) which corresponds to the ILAW previously described in the figure 6. We notice a small peak at 693 MHz (v=5544 m/s) which corresponds to the AlN SAW, with a very low effective coupling. With 2 µm of ZnO the theoretical admittance absolute value shows one peak at 661 MHz (v=5292 m/s) corresponding to the guided acoustic wave.

For thicker ZnO films the resonance frequency of the isolated mode decreases steadily from 592 MHz to 403 MHz (corresponding velocities v= 4742 m/s and v= 3224 m/s). This is mainly due to the lower acoustic velocity of the ZnO compared to AlN and diamond.

The figure 8 shows the normalised Y displacement value for different ZnO thicknesses. Variation step was set to 0.25µm between 1 and 2 µm of ZnO.

The study with fixed AlN thickness value leads also to demonstrates the effect of ZnO thickness on the wave confinement. For thin ZnO layer, 1 µm to 2 µm, the surface displacement at the top of the AlN layers is not negligible but decreases continuously to lower values. The good wave confinement appears only after 2µm for the ZnO layer. For ZnO thicknesses higher than 2 µm we observe that the maximum displacement position move from 2 µm to 4 µm from the ZnO/diamond interface. At 8 µm of ZnO the wave is perfectly confined in the range of 16 µm corresponding respectively to 12 µm in the AlN/ZnO layers and 4 µm in the diamond substrate.

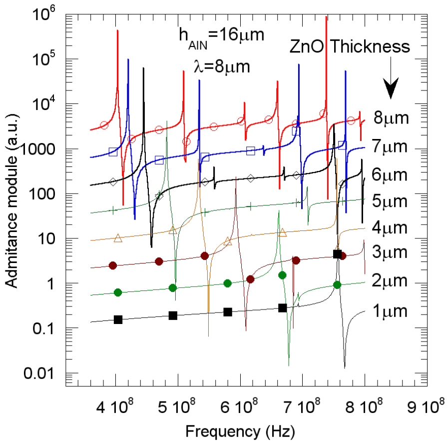


Figure 7. Admitance module of the strucure diamond/ZnO/AlN as function of the frequency for different ZnO thicknesses

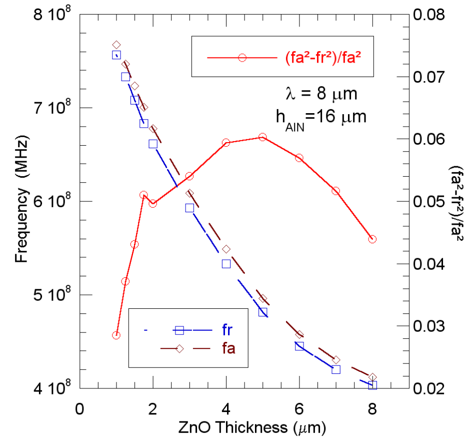


Figure 9. Device resonance fequency (fr) and antiresonance frequency as a function of the AlN thickness and the electromechanical coupling obtained with $(fa^2-fr^2)/fa^2$ formula

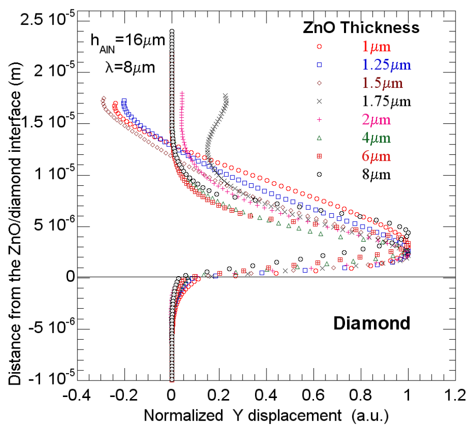


Figure 8. Y direction normalized displacement values for differents ZnO thickness

Dispersion curves of electromechanical coupling and frequency versus ZnO thickness are shown in figure 9. The electromechanical coupling values varied between 3% and 6%, which are almost reasonable theoretical values. The optima values (around 6%) are obtained in a wide range of ZnO thickness (4-6 µm). For higher ZnO thicknesses the electromechanical coupling decreases. These values show that for this structure the maximum coupling is obtained for ZnO thicknesses ranging from λ/2 to 3λ/4.

III. Conclusion

To summarize this work, we have shown that isolated waves with K^2 of 6% propagates in AlN/ZnO/diamond layered structure. Minimum AlN thickness of 3λ/2 is required to obtain the wave confinement. The ZnO thickness is also a key point of the structure and an optimal coupling of 6% is obtained for ZnO thicknesses between λ/2 and 3λ/4. We also demonstrate this AlN/ZnO/diamond structure a better confinement is obtained when ZnO thickness exceeds λ/4.

In addition to the possibility of developing inexpensive encapsulation, this structure presents again the efficiency of diamond for acoustic waves, mainly due to its high acoustic velocity.

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