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Lamb Wave Characteristics of AlN/Diamond Composite Plates with Distinct Electrode Arrangements

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1. Introduction

Recently, piezoelectric Lamb wave resonators utilizing the lowest order symmetric (S_0) mode have attracted many attentions because the mode can provide some superior properties like high acoustic phase velocity, small velocity dispersion, and low motional resistance [1-2]. Limited by the piezoelectric material properties, Lamb wave resonators based on a single piezoelectric layer still have some intrinsic drawbacks, such as the low quality factor and small phase velocity. Several significant research efforts are ongoing to enhance the quality factor of the piezoelectric Lamb wave devices by attaching a low acoustic loss substrate layer, such as Si [3] and SiC [4-5], to the piezoelectric film. In addition, compared to the AlN film, ZnO film exhibts a lower S_0 Lamb wave mode velocity below 6000 m/s; therefore, the nanocrystalline diamond films were used as the substrate layer to increase the resonant frequency of ZnO-on-diamond Lamb wave resonators [6]. It is clear that the composite laminates including a functional substrate layer can improve the performances of Lamb wave devices markedly.

Diamond has the highest acoustic wave velocity and the largest product of frequency and quality factor ($f{\cdot}Q$) among all materials [7]. Combined with a diamond substrate layer, the piezoelectric Lamb wave devices can provide benefits of high Q as well as high operating frquency. Therefore, this study aims to investigate theretically Lamb wave characteristics in multilayered piezoelectric plates including a diamond layer. The formulae of effective permittivity were derived based on the transfer matrix method [3] and further employed to calculate the phase velocity dispersion. Detailed calculations were carried out on the AlN/diamond composite plates with distinct electrode arrangements. The electromechanical coupling coefficients (ECCs) were further calculated exactly by the Green's function method. Finally, the AlN/Si and AlN/SiC composite plates were also analyzed and discussed for comparison.

2. Calculation results

The AlN thin film is a popular piezoelectric material widely used for configuring electro-acoustic devices because of higher velocity and better chemical stability than ZnO film. Therefore, an AlN/diamond multilayered plate is taken as the calculation example. The ratio of the diamond layer thickness to wavelength remains 1. In addition, there are four electrode arrangements, shown in **Fig. 1**, in the calculation: the interdigital transducers (IDTs) are deposited on top surface and the interface can be either electrically free or metalized; moreover, the IDTs are deposited on the interface and the top surface can be either electrically free or metalized. The metalization means zero potential and no mechanical loading.

Figure 2 shows the phase velocity dispersion curves of the S_0 mode Lamb waves for AlN and AlN/diamond multilayered plates. The results indicate that the increasing of diamond layer thickness leads to a larger velocity because of a larger contribution of the diamond layer to the propagation. The phase velocity increases towards 11 km/s, much larger than surface wave velocity of conventional piezoelectric materials like quartz, LiNbO3, and LiTaO3. Moreover, unlike the overtone modes of a diamond SAW device, the S_0 mode Lamb wave is not a leaky mode and has no propagation loss.

Figure 3 shows the ECCs for the four electrode arrangements, calculated by using the Green's function method. The ECCs exhibits a deep dependance on the electrode arrangement. It is worth noting that the ECC of the S_0 mode with the electrode arrangements of type D is larger than that of other electrode arrangements. Moreover, the S_0 mode yields a phase velocity of 10,288 m/s and large ECC of about 2.0% at h/λ=0.29 and H/λ=1. Such characteristics make the AlN/diamond Lamb wave device preferable for high-frequency and high-Q oscillator applications.

For comparison, two conventioal Lamb wave devices based on low-loss substrate layers, such as Si and SiC, were also calculated and discussed. **Fig. 4** depicts the phase velocity dispersion curves of the S_0 mode Lamb waves for the three multilayered plates. The AlN/diamond plate exhibits the largest phase velocity due to the highest acoustic wave velocity of diamond layer. **Fig. 5** shows the ECCs for the AlN/Si and AlN/SiC composite plates. The EECs are much smaller than that of the AlN/diamond plate.

3. Conclusions

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Phase velocity and EEC of S_0 mode Lamb wave in the AlN/diamond multilayered plate with distinct electrode arrangements were investigated theoretically using the effective permittivity method and the Green's function method. Results show the phase velocities of the S_0 mode Lamb wave are indeed increased by including the diamond layer. In the AlN/diamond structure, the S_0 mode yields a phase velocity of 10,288 m/s and ECC of about 2.0% at h/λ=0.29 and H/λ=1, which are better than the AlN/Si and AlN/SiC plates. Such favorable characteristics contribute to realize the AlN/diamond Lamb wave device as a high-Q oscillator with a resonance frequency up to several GHz without a sub-micrometer lithographic resolution.

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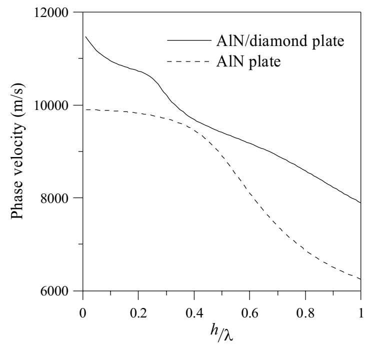


Fig. 2 Phase velocity dispersions of the S_0 mode Lamb wave for AlN and AlN/diamond plates.

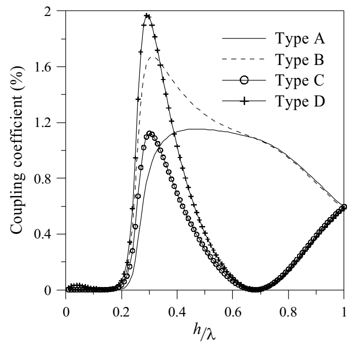


Fig. 3 Coupling coefficients of the S_0 mode Lamb wave for AlN/diamond plate.

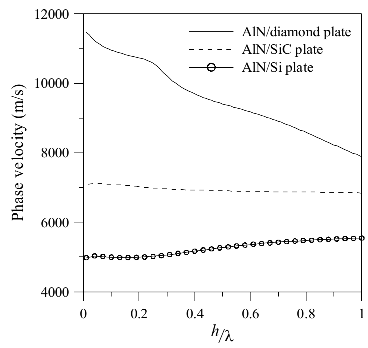


Fig. 4 Phase velocity dispersions of the S_0 mode Lamb wave for AlN/diamond, AlN/SiC, and AlN/Si plates.

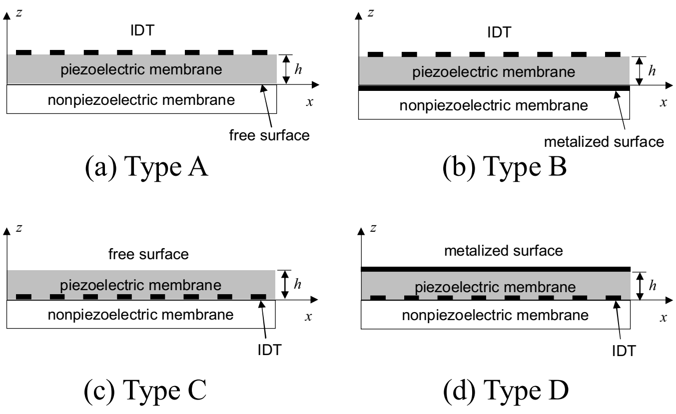
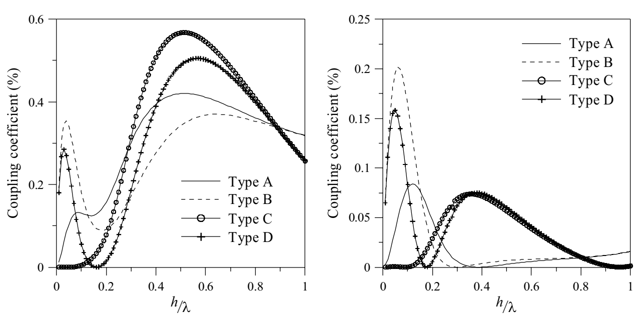


Fig. 1 Four types of electrode arrangements.



(a) (b)

Fig. 5 Coupling coefficients of the S_0 mode Lamb wave for (a) AlN/Si and (b) AlN/SiC plates.