Exact analysis of dispersive SAW devices on ZnO/Diamond/Si layered structures

T.-T. Wu and Y.-Y. Chen
Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan
E-mail: wutt@spring.iam.ntu.edu.tw

Abstract - A formulation for calculating the effective permittivity of a piezoelectric layered SAW structure is given and the exact frequency response of ZnO/Diamond/Si layered SAW calculated. The frequency response of an unapodised SAW transducer is calculated and the center frequency shift due to the velocity dispersion explained. In addition, the electromechanical coupling coefficients of the ZnO/Diamond/Si layered half space based on two different formulae are calculated and discussed. Finally, based on the results of the study, we propose a method for modeling the layered SAW device. The advantage of using the effective permittivity method is that not only the null frequency bandwidth but also the center frequency shift and insertion loss can be evaluated.

I. Introduction

Propagation of surface waves in layered structures has been of interest in the development of dispersive surface acoustic wave (SAW) devices. By including a high velocity diamond layer between a piezoelectric layer and a Si substrate, the surface wave velocity can be increased significantly [1,2]. This results in an increase of the SAW frequency without decreasing the electrode spacing into the sub-micron region.

In the last decade, there are experimental as well as theoretical investigations on the layered SAW. In the theoretical calculation, based on the matrix method, Adler and Solie [3] calculated the electromechanical coupling of layered SAW with ZnO on Diamond. In the calculations, different boundary conditions were considered. By using the conventional approach for calculating surface wave dispersion, Nakahata et al. [4] reported analyses of phase velocity and electromechanical coupling coefficient for three different layered SAWs with diamond as the middle layer. As to the modeling of SAW transducer, Hachigo and Malocha [5] used the delta function model to calculate the null frequency bandwidth of ZnO/Diamond/Si layered SAW and found the reduction of the bandwidth due to velocity dispersion. In addition, they presented the dispersive equivalent circuit model for layered structures.

In this paper, the effective permittivity and phase velocity dispersion of a ZnO/Diamond/Si layered half space (shown in Figure 1) was calculated based on the matrix method [6-9]. The frequency response of an unapodised SAW transducer was then calculated based on the effective permittivity method and discussions were given on the shifting of the center frequency. The electromechanical coupling coefficients of the ZnO/Diamond/Si layered half space based on two different formulae are compared and discussed. Finally, based on the results of the study, we propose an exact analysis for modeling the layered SAW device.

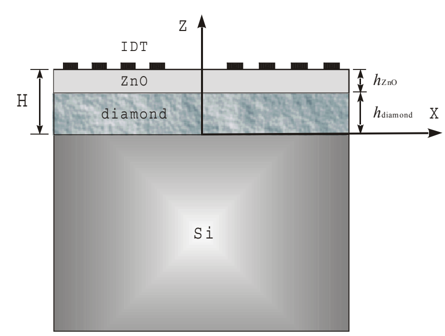

Fig. 1. ZnO/Diamond/Si layered half space

II. Effective permittivity of a layered piezoelectric medium

In the following calculations, we employed a formulation, which is based on the propagator matrix and the surface impedance approach, to calculate the effective permittivity of a layered piezoelectric medium. The detailed derivation of the formulation can be found in reference [10].

Along with the formulation, the effective permittivity at the interface between the vacuum and the ZnO can be expressed as [10]

$$\varepsilon_s = \frac{\bar{D}_Z\big|_{Z=H^+} - \bar{D}_Z\big|_{Z=H^-}}{k_x \bar{\phi}\big|_{Z=H}} = \varepsilon_0 - \frac{\bar{D}_Z\big|_{Z=H^-}}{k_x \bar{\phi}\big|_{Z=H}}, \quad k_x > 0 \qquad (1)$$

where $\bar{D}_z$ and $\bar{\phi}$ are the amplitudes of the normal component of the electric displacement and the electric potential, respectively. k_x is the wave number along the x-direction of the plane harmonic wave.

Since the zeros of the effective permittivity function correspond to the surface wave solution for a free surface, and the poles indicate the surface wave solution for a metallised surface, the phase velocity dispersion can be calculated based on the aforementioned effective permittivity approach. Shown in Figure 2 is the calculated phase velocity dispersion of the first two SAW modes (first mode: thicker solid line; second mode: thinner solid line) of the ZnO/Diamond/Si layered half space with free surface boundary condition while the thickness of the diamond layer was 22 μm and that of the ZnO layer was 0.9 μm. In Figure 2, the thicker dashed line represents the phase velocity dispersion of the first mode of a ZnO/Diamond layered half space and the thinner dashed line is the second mode. The results show that the diamond layer can be treated as a half space so far as fh_{ZnO} value is high enough (In this case, for the first mode the separation fh_{ZnO} value is around 350 m/s). It is worth noting that the dispersion curves of the first two SAW modes come very close to each other, but do not cross as mentioned in [3].

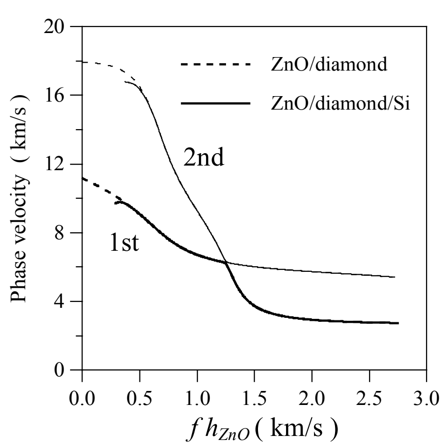

Fig. 2. Phase velocity dispersion

III. Frequency responses of a ZnO/Diamond/Si SAW device

The frequency response of an unapodised transducer using the effective permittivity method can be expressed as [11]

$$H_t(\omega) = (\omega W \Gamma_s)^{\frac{1}{2}} \bar{\rho}_e(\beta) \exp(-\frac{1}{2} j\beta L) \qquad (2)$$

where W is the overlap length of the IDT electrodes and L is the length of the unapodised transducer. The Fourier transform of the electrostatic charge density $\bar{\rho}_e(\beta)$ for IDT transducers with regular electrodes can be found in [12]. The transducer here is the conventional single-electrode type. The wavenumber $\beta(\omega)$ is taken to be $\frac{\omega}{v_0(\omega)}$, where v_0 is the free surface velocity (open circuit velocity). We note that for this layered system, v_0 is a function of frequency ω and can be obtained from the dispersion relation. The function Γ_s is defined as [11]

$$\frac{1}{\Gamma_s} = -\beta \left[\frac{d\varepsilon_s(k_x)}{dk_x} \right]_\beta \qquad (3)$$

Figure 3 shows the frequency responses of an unapodized transducer on a ZnO/Diamond/Si layered structure based on the delta function (dotted line), dispersive delta function (dashed line) [5] and the effective permittivity (solid line) models. The thickness of the diamond layer is 22 μm and that of the ZnO layer is 0.9 μm. The center frequency was chosen at 900MHz, and the number of electrode pairs was 20. The results showed that both the dispersive delta function model and the effective permittivity model could show the reduction of the null frequency bandwidth. A close examine of the frequency response calculated by the effective permittivity model, reveals that there is a center frequency shift from 900 MHz to 901.92 MHz. Calculations show that the function $\sqrt{\Gamma_s}$ is asymmetrical with respect to the center frequency and monotonically increasing. Results reveal that the slightly increase of the center frequency is mainly due to the monotonically increase of $\sqrt{\Gamma_s}$ on the frequency.

IV. The electromechanical coupling coefficient

The electromechanical coupling coefficient K_s^2 can be defined as [13]

$$K_s^2 = 2\Gamma_s \varepsilon_s^{(\infty)} \qquad (4)$$

where $\varepsilon_s^{(\infty)}$ is the effective permittivity at infinite slowness and Γ_s can be calculated exactly from

Eq. (3). On using the Ingebrigtsen approximation [14], the electromechanical coupling coefficient K_s^2 of a piezoelectric medium can be approximated as

$$K_s{}^2 = 2\frac{v_0 - v_m}{v_0} \quad (5)$$

where v_m is the surface wave velocity with metallized surface.

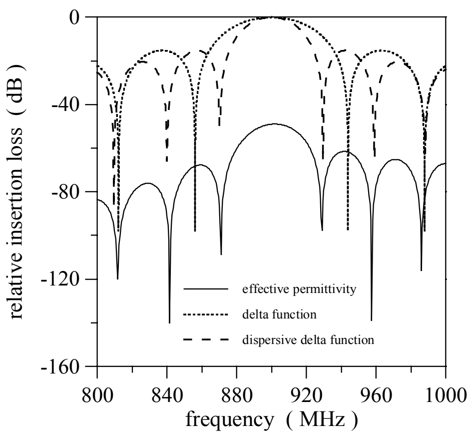

Fig. 3. Frequency responses of an unapodized transducer on a ZnO/Diamond/Si layered structure

The solid lines shown in Figure 4 are portions of the dispersion curves of the ZnO/Diamond/Si layered half space mentioned in Section II. The thicker solid line is the first and the thinner solid line is the second SAW mode. Based on Eq. (4), the electromechanical coupling coefficients for the first two SAW modes are calculated, the thicker dashed line represents that of the first SAW mode, while the thinner dashed line the second SAW mode. The results show that for both modes at fh_{ZnO}=1247 m/s (1386 MHz) where the phase velocity changes sharply is in accordance with the frequency where the electromechanical coupling coefficient changing dramatically. At this sharp change frequency, K_s^2 of the first mode goes to almost zero, while that of the second mode goes to a maximum.

In reference [3], Adler and Solie pointed out that the coupling coefficient calculated at constant frequency is about four times larger than that calculated at constant wavelength. The calculation of the electromechanical coupling coefficient K_s^2 reported is based on the Eq. (5). According to our calculated results, if K_s^2 is calculated using Eq. (4), the difference induced by calculations at constant frequency and constant wavelength disappear. The main difference of Eqs. (4) and (5) is that in Eq. (5), Γ_s is approximated by the Ingebrigtsen's approximation, while in Eq. (4), Γ_s is calculated exactly.

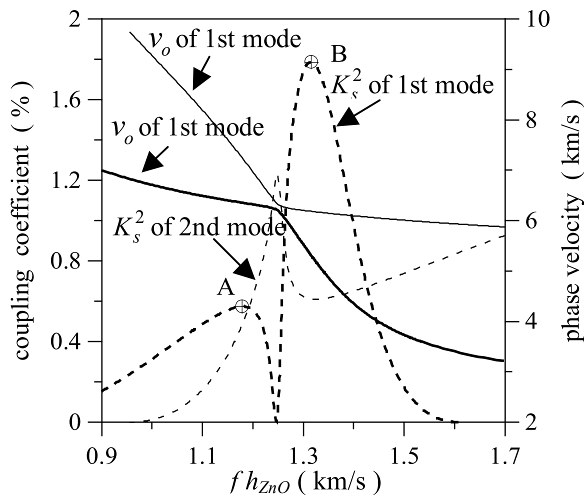

Fig. 4. Electromechanical coupling coefficients and dispersion curves of the first two SAW mode

V. Preliminary design of a dispersive SAW

For the IDT transducer described in section III, the thickness of the ZnO layer was 0.9μm, and the design center frequency was 900 MHz. Previous discussions showed that with this configuration, there is a shift of the center frequency from 900 MHz to 901.92 MHz due to the monotonically increase of $\sqrt{\Gamma_s}$ on the frequency.

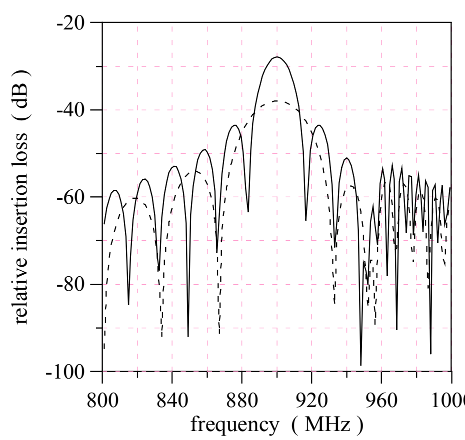

Fig. 5. Frequency response of ZnO/Diamond/Si layered SAW. (f=900MHz, $h_{diamond}$ = 22μm, h_{ZnO} =1.31μm)

To avoid the shifting of the center frequency, the operating frequency of an IDT SAW transducer should be chosen at one of the two local maximums (points A or B) of the coupling coefficient plot shown in Figure 4. For values of the electromechanical coupling coefficient K_s^2 around points A and B are symmetrical with respect to the frequencies of points A and B. Therefore, from Eq. (4), the values of the function $\sqrt{\Gamma_s}$ are also symmetrical. It is worth noting that from Figure 4, the velocity dispersion around the first K_s^2 maximum (point A) is less dispersive as compared with that of the second maximum (point B). So, it is better to choose point A in practice. For example, on choosing the thickness frequency fh_{ZnO} =1179 m/s (point A), the thickness of the ZnO layer is 1.31 μm for a 900 MHz IDT transducer. Figure 5 shows the frequency response of such a layered SAW with 20 and 40 electrode pairs. Results demonstrated that the center frequency is not shifted and is equal to 900 MHz as designed.

VI. Conclusion

An analysis of the ZnO/Diamond/Si layered SAW based on the effective permittivity approach is presented. The formulation based on the matrix method for calculating the effective permittivity of a layered piezoelectric medium is given and used to calculate the phase velocity dispersion and the electromechanical coupling coefficient of the layered system. In the Layered SAW simulation, in addition to the bandwidth narrowing reported in the literature [5], we found that there exists a central frequency shift due to the phase velocity dispersion. On the other hand, in the calculation of the electromechanical coefficient, results show that the sharp change of phase velocity in the dispersion curve is intimately related to the sharp change of the electromechanical coupling coefficient. We show that if the electromechanical coupling coefficient is calculated based on the exact effective permittivity function (Eq. (4)), the coupling coefficients calculated at constant frequency and constant wavelengths are equivalent. Finally, we proposed a method, based on the effective permittivity approach, to design a dispersive SAW transducer with zero center frequency shift and low insertion loss.

VII. Acknowledgment

The authors thank the financial support of this research from the National Science Council of ROC through the grant NSC89-2218-E-002-033.

VIII. References

[1] K. Yamanouchi, N. Sakuri and T. Satoh, "SAW propagation characteristics and fabrication technology of piezoelectric thin film/diamond structure," *Proc. IEEE Ultrason. Symp.*, pp. 351-354, 1989.

[2] H. Nakahata, K. Higaki, A. Hachigo, S. Shikata, N. Fukmori, Y. Takahashi, T. Kajihara, Y. Yamamoto, "High frequency surface acoustic wave filter using ZnO/diamond/Si structure," *Jpn, J. Appl. Phys, Part 1*, **33** (1), 324-328, 1994.

[3] Eric L. Adler and L. Solie, "ZnO on diamond: SAWs and pseudo-SAWs," *Proc. IEEE Ultrason. Symp.*, 341-344, 1995.

[4] H. Nakahata, A. Hachigo, K. Higaki, S. Fujii, S. Shikata, N. Fujimori, "Theoretical study on SAW characteristics of layered structures including a diamond layer," *IEEE Trans.*, *UFFC*, **42** (3), 362-375, 1995.

[5] A. Hachigo, and D. C. Malocha, "SAW device modeling including velocity dispersion based on ZnO/diamond/Si layered structures," *IEEE Trans.*, *UFFC*, **45** (3), 660-665, 1998.

[6] A.N. Stroh, "Steady state problems in anisotropic elasticity," *J. Math. Phys.*, **41**, 77-103, 1962.

[7] A.H. Fahmy and E.L. Adler, "Propagation of acoustic surface waves in multilayers: a matrix description," Appl. Physics Letters, 22 (10), 495-497, May, 1973.

[8] K.A. Ingebrigtsen and A. Tonning, "Elastic surface waves in crystals," *Physical Review.*, **184**(3), 942-951, 1969.

[9] Honein, B.; Braga, A.M.B.; Barbone, P.; Herrmann, G., "Wave Propagation in Piezoelectric Layered Media With Some Applications," *J. Intelligent Material Systems and Structures*, **2**(4), 542-557, 1991.

[10] Wu, T.-T. and Chen, Y.-Y. "Exact analysis of dispersive SAW devices on ZnO/Diamond/Si layered structures," IEEE *UFFC*, (accepted)

[11] D. P. Morgan, *Surface-Wave Devices for Signal Processing*, Elsevier, New York, 1985.

[12] Eq. 4.85 of Ref. 11.

[13] Herbert Matthews, *Surface Wave Filters: Design, Construction, and Use,* Eq. (2.30), p. 66, Wiley, New York, 1977.

[14] K.A. Ingebrigtsen, "Surface waves in piezoelectrics," *J. Appl. Phys.*, **40**, 2681-2686, 1969.