Transverse Acoustic Waves In Finite Piezoelectric-Metal Superlattices

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Abstract: In this communication, we study the propagation of transverse acoustic waves in a finite superlattice (SL) constituted of alternating piezoelectric and metal layers. Our objective is to determine: i) the transmission and reflection coefficients through a finite SL, ii) the confined modes related to the finite size of the SL and iii) the possibility of existence of the acoustic Brewster angle in these systems.
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I. Introduction

The acoustic wave propagation in heterogeneous piezoelectric structures (namely, the piezoelectric superlattices) has received increasing attention in recent decades [1] because of the new physical properties they present in comparison with bulk elastic materials. In this context, the work of Alshit et al. [2] focused on the propagation of acoustic waves in finite SL formed of identical piezoelectric or piezomagnetic layers covered, respectively, by an infinitely thin layer of metal or superconducting. From a practical point of view, superlattices are composed of a finite number of cells deposited on a substrate. These composite structures usually present artificial or natural defects inside these structures such as: a buffer layer (a layer embedded between the substrate and the SL) a cap layer (a layer at the surface of the SL), a cavity layer…, giving rise to new modes that may exist in the gaps separating the bulk bands [3]. Experimentally, the spectra of phonons in solid-solid SLs were studied by Raman scattering [4-6], which allowed the observation, for the first time, of folded branches associated with modes in the first Brillouin zone. Other experiments of Raman scattering were performed on a finite SL made of Si/Ge_mSi_n to examine the interaction between the different modes in substrate/SL/cap layer systems [7]. Some observed peaks have been interpreted as resonant modes associated with the presence of the substrate and the cap layer. Similar studies in $Si\text{-}Ge_{1-x}Si_x$ and GaAs-AlAs SLs have shown the existence of weak peaks in the spectra of folded acoustic phonons [8,9]. These peaks were interpreted as phonons confined in within the SL.

- In this paper we are interested in studying the propagation of acoustic waves of transverse polarization in finite size piezoelectric-metallic SLs. Our objective is to give the dispersion relations of the confined modes, the closed form expressions of the transmission and reflection coefficients and highlight some new results in these systems such as:
- Confined modes related to the finite size of the SL. In particular, the establishment of a rule on the distribution patterns in these systems.
- The possibility of existence of the Brewster acoustic angle.
- The study of transmission and reflection coefficients through a finite SL.

Recently, Chen et al. [10] have studied surface modes in a semi-infinite piezoelectric-metallic SL terminated with a piezoelectric layer at the surface and they deduced the electromechanical coupling coefficient. However, to our knowledge, the study of finite piezoelectric-metallic SL has not been studied previously. In the following, we avoid giving the details of the method of calculation which is based on the Green's function [3]. The analytical expressions of dispersion relations of the confined modes as well as the transmission and reflection coefficients will be presented elsewhere.

II. Numerical results and discussions

In what follows, we give some illustrations for the band gap structure sketched in the first Brillouin zone and the eigenmodes in a finite piezoelectric-metal SL. Our goal is to show the possibility of existence of the Brewster angle in the metal-piezoelectric SL. Then we consider the transmission spectrum through a finite SL sandwiched between two similar metals.

In Figures 1 (a) and (b), we give the complex band gap structure within the first Brillouin zone for an infinite PZT4-Fe SL for two incident angles: $\theta = 0°$ (Fig. 1 (a)) and $\theta = 40°$ (Fig. 1 (b)). Dashed and continuous curves correspond to the situations where the piezoelectricity in PZT4 layers is present and absent respectively. The existence of the allowed and prohibited bands in these structures has been demonstrated recently [10]. The thicknesses of piezoelectric and metallic layers in the SL are assumed to be equal, $d_p = d_m$, and the period of the SL is $D = d_m + d_p = 2d_m$. The numerical values of elastic, dielectric,

piezoelectric constants and mass density of the materials used in this communication are given in reference [4]. In both figures 1 (a) and (b), we see a large gap between the band structures when considering the piezoelectricity. Figures 1 (c) and (d) show the transmission spectra through a finite SL composed of N = 5 cells for the same structures as in Figures 1 (a) and (b). The transmission spectra exhibit oscillations within the allowed bands. Despite the low number of layers in the SL (N = 5), we note that the positions of dips in the transmission spectra reflect the position of the forbidden zones of the infinite structure (Figs. 1 (a) and (b)). An interesting result that could be deduced from these figures is the existence of regions of frequencies where the gaps of the band structures without piezoelectricity coincide with the allowed bands of the band structures when taking into account the piezoelectricity (see Figures 1 (a) around $\omega D / v_t(Fe) = 4.2$ and Figure 1 (b) around $\omega D / v_t(Fe) = 4.7$). This result can be used to design an on / off switch for the transmission of waves in certain frequency regions by manipulating the piezoelectricity in PZT4 layers.

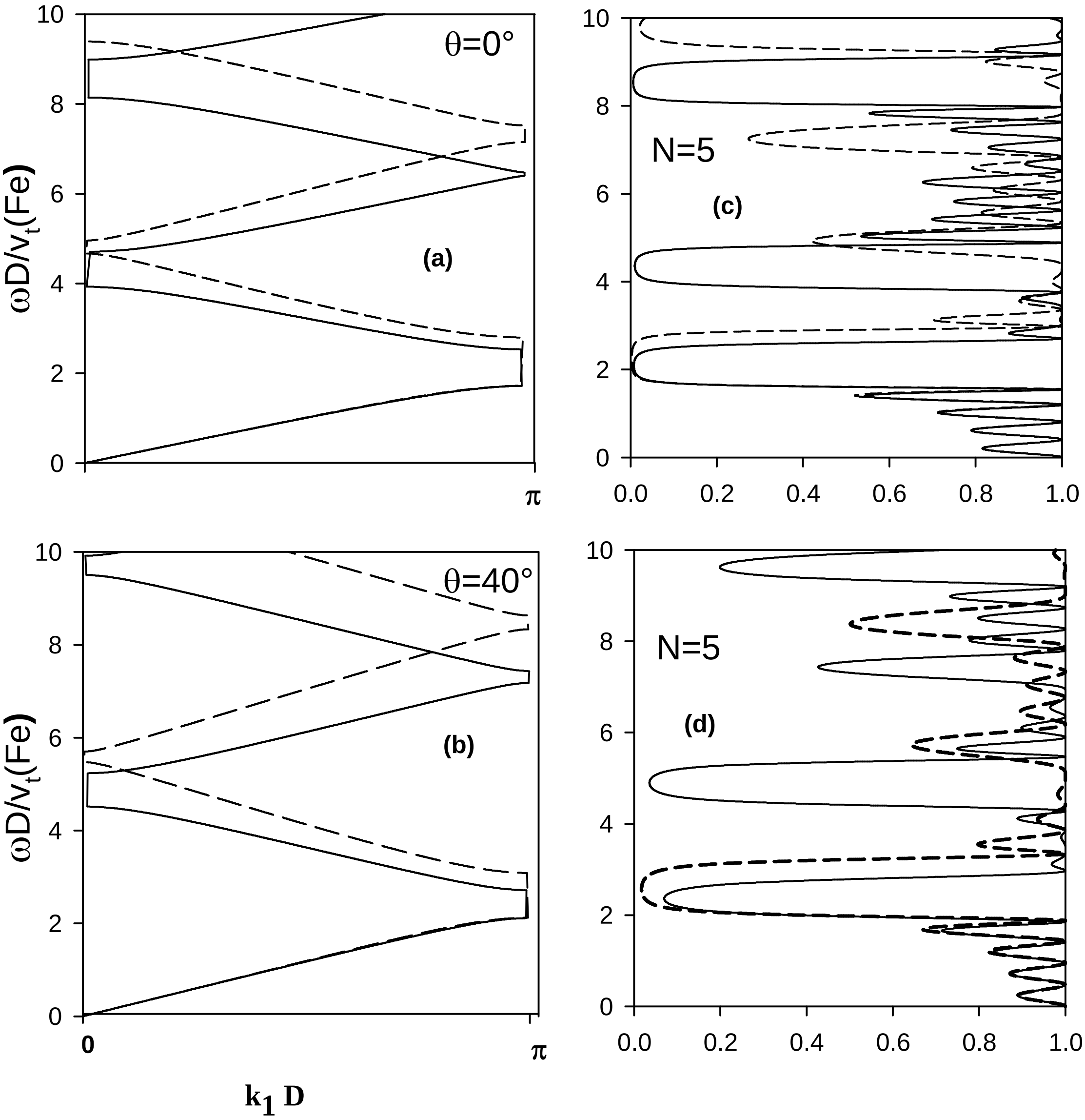

Figure 1: (a) and (b) Represents the complex band structures of CT PZT4-Fe within the first Brillouin zone for angles of incidence: normal (θ=0 °) and oblique (θ = 40 °) respectively. (C) and (d) Represents the variation of the transmission coefficient through a finite CT composed of N = 5 cells. discontinuous curves (solid) correspond with the CT (ignoring) of piezoelectricity in layers PZT4.

A more interesting result can be obtained when the incident wave is sent under the Brewster angle in the absence of piezoelectricity. This is illustrated in Figures 2 (a) and (b) by solid lines. Note the band closing at the Brillouin zone boundaries of and a total transmission through the structure. Now, when considering the piezoelectricity in the PZT4 layers, there gaps open at the limits of the Brillouin zone and hollow areas appear in the transmission spectra. These hollows tend to zero gradually as the number of cells in the SL increases (see Fig. 2 (b)). This result clearly shows that the piezoelectricity stops the existence of the Brewster angle and allows the creation of closed areas that block the propagation of the waves at certain frequencies.

To give a more comprehensive view on the evolution of the maxima of transmission coefficients (or reflection zero), we have shown in Figures 3 (a) and (d) discrete modes corresponding to the reflection zeros. The figures on the top (bottom) panel in Figure 3 correspond to a piezoelectric-metal SL where the piezoelectric layers are considered without (with) piezoelectricity. Notice that we have N-1 modes within each band; these modes are represented by dots. The number of branches depends on the number of cells forming the SL. As the number of cells is growing, construction of bulk bands becomes more pronounced resulting in a continuum in the limit where N tends to infinity (shaded in gray areas).

Other modes (open circles) are also reflection zeros of a single piezoelectric plate sandwiched between two metals. In the absence of piezoelectricity, the modes in open circles fall on the Brewster line. Along this line, we can expect closing gaps. However, in the presence of piezoelectricity, we obtain a lifting of degeneracy and an anti-crossing of bands around the points of closing gaps. These anti-crossings are becoming progressively weaker as the piezoelectric constant becomes low as it is shown in Figures 3 (e) and (f) for ZnO-Fe and CdS-Fe SLs, respectively.

III. Conclusion

In this paper, we have studied the propagation of acoustic waves of transverse polarization in the finite size SLs made of piezoelectric-metal layers. We have performed analytical calculations (not presented here) of the Green's function of a finite SL. We were able to deduce the transmission and reflection coefficients, which allowed us to study the dispersion modes confined within a finite SL inserted between two metal substrates.

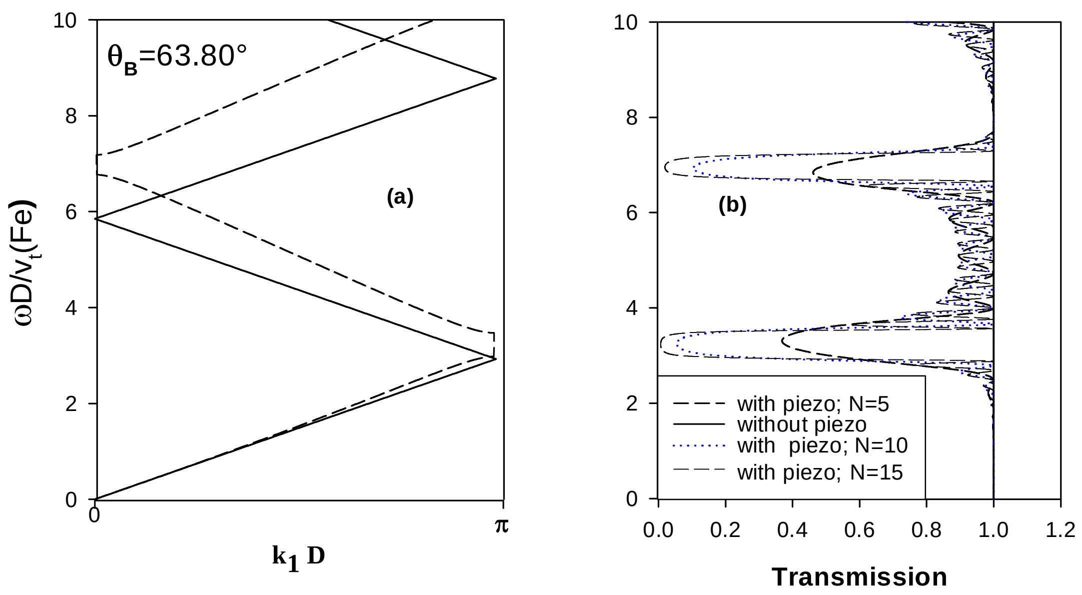

Figure 2: The same as figure 1 but for the Brewster angle (θ_B = 63.80 °) of PZT4-Fe superlattice. (b) Variation of the transmission coefficient for different values of the number N of cells in the SL.

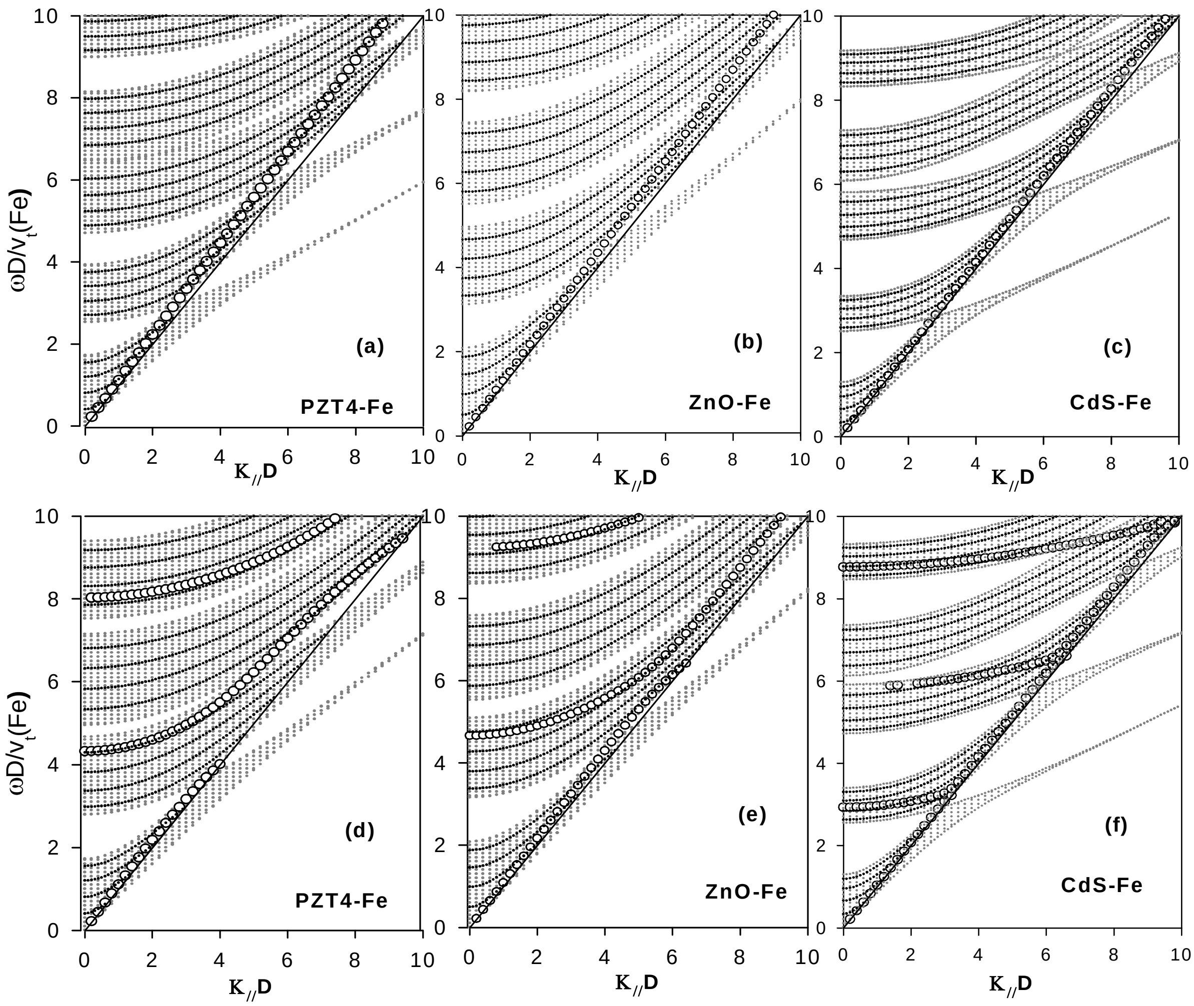

Figure 3: Projected band gap structures for PZT4-Fe SL [Figs (a), (d)], ZnO-Fe [Figs (b), (e)], CdS-Fe [Figs (c), (f)]. The gray shaded areas represent the allowed bands of an infinite SL. Continuous branches and open circles correspond to the reflection zeros of a finite SL composed of N = 5 cells. In each figure, lines represent the sound speed of the Fe metal.

We have shown the existence of confined modes in a finite SL constituted of N cells and inserted between two metallic substrates. In particular, we showed that there are N-1 modes within each allowed band and other modes associated with a piezoelectric plate inserted between two metals. These modes give rise to anti-crossings in the presence of piezoelectricity. An interesting result is the disappearance of the Brewster angle in the presence of piezoelectricity in piezoelectric-metal SL. This result can be used to make such structures as rejection filters in certain ranges of frequencies.

VI. References

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