

Interface waves between two piezoelectric half-spaces with a semiconductor film

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Abstract: In this work propagation of anti-plane (SH) waves in two piezoelectric ceramic half-spaces with a thin layer of a semiconducting material between the half-spaces is studied, and wave attenuation and dispersion caused by semiconduction as well as wave amplification by a biasing electric field are examined.

Key words: Piezoelectricity, Semiconductor, Wave, Attenuation, Dispersion

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INTRODUCTION

Piezoelectric materials are either dielectrics or semiconductors (Auld, 1973). An acoustic wave propagating in a piezoelectric crystal is usually accompanied by an electric field. When the crystal is also semiconducting, the electric field produces currents and space charge resulting in dispersion and acoustic loss (Hutson and White, 1962). The interaction between a traveling acoustic wave and mobile charges in piezoelectric semiconductors is called acoustoelectric effect which is a special case of a more general phenomenon called wave-particle drag (Weinreich *et al.*, 1959). It was found that an acoustic wave traveling in a piezoelectric semiconductor can be amplified by the application of a dc electric field (White, 1962). This phenomenon is called acoustoelectric amplification of acoustic waves. The acoustoelectric effect and amplification of acoustic waves can also be achieved in composite structures of piezoelectric dielectrics and nonpiezoelectric semiconductors (Dietz *et al.*, 1988). In these composites the acoustoelectric effect is due to the combination of the piezoelectric effect and semiconduction in each component phase. The acoustoelectric effect and acoustoelectric amplification of acoustic waves have

led to the development of acoustoelectric devices (Dietz *et al.*, 1988; Kino, 1976; Heyman, 1978; Busse and Miller, 1981). Both surface acoustic waves (SAW) and bulk acoustic waves (BAW) have been used for acoustoelectric devices. The basic behavior of piezoelectric semiconductors and the acoustoelectric effect can be described by a linear phenomenological theory (Hutson and White, 1962; White, 1962). More sophisticated nonlinear theories for deformable semiconductors had also been developed (de Lorenzi and Tiersten, 1975; Maugin and Daher, 1986). Due to multi-field coupling and anisotropy, device modeling by these theories presents complicated mathematical problems. Exact analysis is possible only in rare cases, e.g., the one-dimensional problem of thickness vibrations of plates (Wauer and Suherman, 1997). In this work we study the propagation of anti-plane waves near the interface between two piezoelectric ceramic half-spaces with a thin layer of a nonpiezoelectric semiconductor between them. Following a summary of the three-dimensional equations of linear piezoelectric semiconductors, two-dimensional equations for a thin piezoelectric semiconductor film are given to model the semiconductor layer. Propagation of anti-plane waves under a dc field is then analyzed. Frequency equations that determine the

dispersion relations are obtained. An approximate analytical solution of the frequency equations and numerical results are presented. Finally, some conclusions are drawn.

THREE-DIMENSIONAL EQUATIONS

Consider a homogeneous, one-carrier piezoelectric semiconductor under a uniform dc electric field \bar{E}_j . The steady state current is $\bar{J}_i = q\bar{n}\mu_{ij}\bar{E}_j$. The conventional summation for repeated tensor indices is used. When an acoustic wave propagates through the material, perturbations of the electric field, the carrier density and the current are denoted by E_j , n and J_i . The linear theory for small signals involves the equations of motion, Gauss's law, and the principle of conservation of charge (Hutson and White, 1962; Wauer and Suherman, 1997):

$$T_{ji,j} = \rho\ddot{u}_i, \quad D_{i,i} = qn, \quad q\dot{n} + J_{i,i} = 0, \quad (1)$$

where a comma followed by an index denotes partial differentiation with respect to the coordinate associated with the index. A superimposed dot represents differentiation with respect to time. The above equations are accompanied by the following constitutive relations (White, 1962)

$$\begin{aligned} T_{ij} &= c_{ijkl}S_{kl} - e_{kij}E_k, \quad D_i = e_{ijk}S_{jk} + \varepsilon_{ij}E_j, \\ J_i &= q\bar{n}\mu_{ij}E_j + qn\mu_{ij}\bar{E}_j - qd_{ij}n_{,j}, \end{aligned} \quad (2)$$

where

$$S_{ij} = (u_{i,j} + u_{j,i})/2, \quad E_i = -\phi_{,i}. \quad (3)$$

With successive substitutions from Eqs.(2) and (3), Eq.(1) can be written as three equations involving u , ϕ and n

$$\begin{aligned} c_{ijkl}u_{k,lj} + e_{kij}\phi_{,kj} &= \rho\ddot{u}_i, \quad e_{ikl}u_{k,li} - \varepsilon_{ij}\phi_{,ij} = qn, \\ \dot{n} - \bar{n}\mu_{ij}\phi_{,ij} + \mu_{ij}\bar{E}_j n_{,i} - d_{ij}n_{,ij} &= 0. \end{aligned} \quad (4)$$

On the boundary of a finite body with a unit outward normal n_i , the mechanical displacement u_i , the traction vector $T_{ij}n_i$, the electric potential ϕ , the normal component of the electric displacement vector $D_i n_i$, the carrier density n and the normal current $J_i n_i$ may

be prescribed on the boundary of a finite body (Wauer and Suherman, 1997).

EQUATIONS FOR A THIN FILM

Consider a piezoelectric semiconductor film of thickness $2h$ as shown in Fig.1 with the coordinate system. The film is assumed to be very thin. We need a two-dimensional theory for the film in the manner of the equations for generalized plane stress in elasticity (Sokolnikoff, 1956). The dominating stress components of this film are T_{11} , T_{33} and T_{13} . We make the usual stress relaxation

$$T_{2j} = 0, \quad j = 1, 2, 3. \quad (5)$$

According to the compact matrix notation (Tiersten, 1969a), with the range of p as 1, 2, ..., and 6, Eq.(5) can be written as

$$T_p = 0, \quad p = 2, 4, 6. \quad (6)$$

For convenience we introduce a convention that subscripts u, v, w take the values 2, 4, 6 while subscripts r, s, t take the remaining values 1, 3, 5. Then Eq.(2)_{1,2} can be written as

$$\begin{aligned} T_r &= c_{rs}S_s + c_{ru}S_u - e_{kr}E_k, \\ T_v &= c_{vs}S_s + c_{vw}S_w - e_{kv}E_k = 0, \\ D_i &= e_{is}S_s + e_{iu}S_u + \varepsilon_{ij}E_j, \end{aligned} \quad (7)$$

where Eq.(6) has been used. From Eq.(7)₂ we have

$$S_u = -c_{uv}^{-1}c_{vs}S_s + c_{uv}^{-1}e_{kv}E_k \quad (8)$$

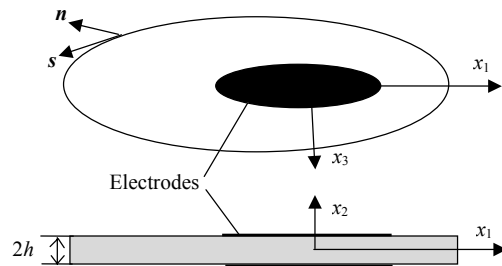


Fig.1 Plan view and cross section of a thin film of piezoelectric semiconductor

Substitution of Eq.(8) into Eq.(7)_{1,3} yields the mechanical and electric constitutive relations for the film

$$T_r = \bar{c}_{rs} S_s - \bar{e}_{kr} E_k, \quad D_i = \bar{e}_{is} S_s + \bar{\varepsilon}_{ij} E_j, \quad (9)$$

whose material constants are

$$\begin{aligned} \bar{c}_{rs} &= c_{rs} - c_{rv} c_{vw}^{-1} c_{ws}, & \bar{e}_{ks} &= e_{ks} - e_{kv} c_{vw}^{-1} c_{vs}, \\ \bar{\varepsilon}_{kj} &= \varepsilon_{kj} + e_{kv} c_{vw}^{-1} e_{jv} \end{aligned} \quad (10)$$

We now introduce another convention that subscripts a, b, c and d assume 1 and 3 but not 2. Then Eq.(9) can be written as

$$T_{ab} = \bar{c}_{abcd} S_{cd} - \bar{e}_{kab} E_k, \quad D_i = \bar{e}_{iab} S_{ab} + \bar{\varepsilon}_{ij} E_j \quad (11)$$

Integrating the equations in Eq.(1)₁ for $i=1, 3$ and Eq.(1)_{2,3} with respect to x_2 through the film thickness, we obtain the following two-dimensional equations of motion, Gauss's law and the conservation of charge:

$$\begin{aligned} T_{ab,a} + \frac{1}{2h} [T_{2b}(x_2 = h) - T_{2b}(x_2 = -h)] &= \rho \ddot{u}_b, \\ D_{a,a} + \frac{1}{2h} [D_2(x_2 = h) - D_2(x_2 = -h)] &= qn, \\ q\dot{n} + J_{a,a} + \frac{1}{2h} [J_2(x_2 = h) - J_2(x_2 = -h)] &= 0, \end{aligned} \quad (12)$$

where u_a, T_{ab}, D_a, J_a and n are averages of the corresponding three-dimensional quantities along the film thickness.

INTERFACE WAVES

Consider two piezoelectric half-spaces of polarized ceramics with a semiconductor film of silicon between them (Fig.2). Silicon is a cubic crystal with m3m symmetry and without piezoelectric coupling. The film is assumed to be very thin as compared to the wavelength we are interested in, and can be modeled by the film equations in the previous section. In this case the equations of the thin film will appear as interface continuity conditions between the half-spaces. This type of approximation had been used to model surface waves guided by thin elastic films (Tiersten, 1969b). For ceramics poled in the x_3 direction we have

$$\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{21} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{31} & c_{31} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix}, \quad \begin{pmatrix} 0 & 0 & e_{31} \\ 0 & 0 & e_{31} \\ 0 & 0 & e_{33} \\ 0 & e_{15} & 0 \\ e_{15} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}^T, \quad (13)$$

$$\begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{pmatrix},$$

where $c_{66} = (c_{11} - c_{12})/2$ (Tiersten, 1969a). We are interested in anti-plane motions with

$$u_1 = u_2 = 0, \quad u_3 = u_3(x_1, x_2, t), \quad \phi = \phi(x_1, x_2, t) \quad (14)$$

The non-vanishing strain and electric field components are

$$\begin{cases} 2S_{13} \\ 2S_{23} \end{cases} = \nabla u_3, \quad \begin{cases} E_1 \\ E_2 \end{cases} = -\nabla \phi, \quad (15)$$

where $\nabla = \mathbf{i}_1 \partial_1 + \mathbf{i}_2 \partial_2$ is the two-dimensional gradient operator. The nontrivial components of T_{ij} and D_i are

$$\begin{cases} T_{13} \\ T_{23} \end{cases} = c_{44} \nabla u_3 + e_{15} \nabla \phi, \quad \begin{cases} D_1 \\ D_2 \end{cases} = e_{15} \nabla u_3 - \varepsilon_{11} \nabla \phi \quad (16)$$

The nontrivial components of the equations of motion and charge take the following form:

$$c_{44} \nabla^2 u_3 + e_{15} \nabla^2 \phi = \rho \ddot{u}_3, \quad e_{15} \nabla^2 u_3 - \varepsilon_{11} \nabla^2 \phi = 0, \quad (17)$$

where ∇^2 is the two-dimensional Laplacian $\nabla^2 = \partial_1^2 + \partial_2^2$. Introducing (Bleustein, 1968)

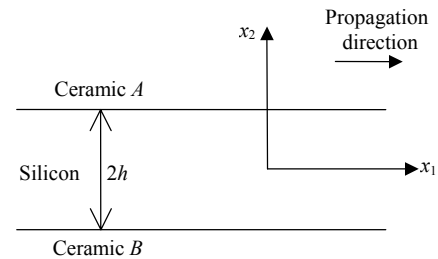


Fig.2 Two ceramic half-spaces with a semiconductor film

$$\psi = \phi - \frac{e_{15}}{\varepsilon_{11}} u_3, \tag{18}$$

then

$$\begin{aligned} T_{23} &= \bar{c}_{44} u_{3,2} + e_{15} \psi_{,2}, \quad T_{31} = \bar{c}_{44} u_{3,1} + e_{15} \psi_{,1}, \\ D_1 &= -\varepsilon_{11} \psi_{,1}, \quad D_2 = -\varepsilon_{11} \psi_{,2}, \end{aligned} \tag{19}$$

and

$$\bar{c}_{44} \nabla^2 u_3 = \rho \ddot{u}_3, \quad \nabla^2 \psi = 0, \tag{20}$$

where

$$\bar{c}_{44} = c_{44} + \frac{e_{15}^2}{\varepsilon_{11}} = c_{44} (1 + k_{15}^2), \quad k_{15}^2 = \frac{e_{15}^2}{\varepsilon_{11} c_{44}} \tag{21}$$

Fields in the upper half-space

For the upper half-space, the solution can be written as

$$\begin{aligned} u_A &= U e^{-\eta_A x_2} \exp i(\xi x_1 - \omega t), \\ \psi_A &= \Psi_A e^{-\xi x_2} \exp i(\xi x_1 - \omega t), \end{aligned} \tag{22}$$

where U and Ψ_A are undetermined constants,

$$\eta_A^2 = \xi^2 - \frac{\rho_A \omega^2}{\bar{c}_A} = \xi^2 \left(1 - \frac{v^2}{v_A^2} \right) > 0, \tag{23}$$

and

$$v = \omega / \xi, \quad v_A^2 = \bar{c}_A / \rho_A. \tag{24}$$

For continuity conditions, we need ϕ_A , T_{23} and D_2 in ceramic A . We denote T_{23} and D_2 by T_A and D_A :

$$\begin{aligned} \phi_A &= \psi_A + \frac{e_A}{\varepsilon_A} u_A \\ &= (\Psi_A e^{-\xi x_2} + \frac{e_A}{\varepsilon_A} U e^{-\eta_A x_2}) \exp i(\xi x_1 - \omega t), \\ T_A &= \bar{c}_A u_{A,2} + e_A \psi_{A,2} \\ &= -(\bar{c}_A \eta_A U e^{-\eta_A x_2} + e_A \xi \Psi_A e^{-\xi x_2}) \exp i(\xi x_1 - \omega t), \\ D_A &= -\varepsilon_A \psi_{A,2} = \varepsilon_A \xi \Psi_A e^{-\xi x_2} \exp i(\xi x_1 - \omega t). \end{aligned} \tag{25}$$

Fields in the lower half-space

Similarly, for the lower half-space, the solutions can be written as

$$\begin{aligned} u_B &= U e^{\eta_B x_2} \exp i(\xi x_1 - \omega t), \\ \psi_B &= \Psi_B e^{\xi x_2} \exp i(\xi x_1 - \omega t), \end{aligned} \tag{26}$$

where

$$\eta_B^2 = \xi^2 - \frac{\rho_B \omega^2}{\bar{c}_B} = \xi^2 \left(1 - \frac{v^2}{v_B^2} \right) > 0, \tag{27}$$

$$v_B^2 = \bar{c}_B / \rho_B. \tag{28}$$

Note that the continuity of u between the two half-spaces is already satisfied. For the other continuity conditions, we need ϕ_B , T_{23} and D_2 in ceramic B . We denote T_{23} and D_2 by T_B and D_B :

$$\begin{aligned} \phi_B &= \psi_B + \frac{e_B}{\varepsilon_B} u_B \\ &= \left(\Psi_B e^{\xi x_2} + \frac{e_B}{\varepsilon_B} U e^{\eta_B x_2} \right) \exp i(\xi x_1 - \omega t), \\ T_B &= \bar{c}_B u_{B,2} + e_B \psi_{B,2} \\ &= (\bar{c}_B \eta_B U e^{\eta_B x_2} + e_B \xi \Psi_B e^{\xi x_2}) \exp i(\xi x_1 - \omega t), \\ D_B &= -\varepsilon_B \psi_{B,2} = -\varepsilon_B \xi \Psi_B e^{\xi x_2} \exp i(\xi x_1 - \omega t). \end{aligned} \tag{29}$$

Fields in the film

For long waves, fields in the semiconductor film can be treated as functions of x_1 and time only. Denote the fields in the film by

$$\begin{aligned} u &= U \exp i(\xi x_1 - \omega t), \quad \phi = \Phi \exp i(\xi x_1 - \omega t), \\ n &= N \exp i(\xi x_1 - \omega t) \end{aligned} \tag{30}$$

where Φ and N are undetermined constants. Eq.(30) already satisfies the continuity of mechanical displacement between the film and the ceramic half-spaces. We use a prime to indicate the elastic and dielectric constants as well as the mass density of the film. The elastic and dielectric constants are given by

$$\begin{pmatrix} c'_{11} & c'_{12} & c'_{12} & 0 & 0 & 0 \\ c'_{12} & c'_{11} & c'_{12} & 0 & 0 & 0 \\ c'_{12} & c'_{12} & c'_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & c'_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c'_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c'_{44} \end{pmatrix}, \begin{pmatrix} \varepsilon'_{11} & 0 & 0 \\ 0 & \varepsilon'_{11} & 0 \\ 0 & 0 & \varepsilon'_{11} \end{pmatrix}. \tag{31}$$

Consider the case when the dc biasing electric field is in the x_1 direction. From Eqs.(30), (31), (11) and (2); we obtain

$$T_{13} = \bar{c}'_{55} S_{13} = \bar{c}'_{44} u_{3,1} = \bar{c}'_{44} i \xi U e^{i(\xi x_1 - \omega t)},$$

$$\begin{aligned}
D_1 &= \bar{\varepsilon}'_{11} E_1 = -\bar{\varepsilon}'_{11} \phi_{,1} = -\bar{\varepsilon}'_{11} i \xi \Phi e^{i(\xi x_1 - \omega t)}, \\
J_1 &= -q \bar{n} \mu_{11} \phi_{,1} + q n \mu_{11} \bar{E}_1 - q d_{11} n_{,1} \\
&= (-q \bar{n} \mu_{11} i \xi \Phi + q N \mu_{11} \bar{E}_1 - q d_{11} i \xi N) e^{i(\xi x_1 - \omega t)} \quad (32)
\end{aligned}$$

Continuity conditions

From the continuity of the electric potential and Eq.(12), we have

$$\begin{aligned}
\Psi_A + \frac{e_A}{\varepsilon_A} U &= \Phi, \quad \Psi_B + \frac{e_B}{\varepsilon_B} U = \Phi, \\
-\bar{c}'_{44} \xi^2 U + \frac{1}{2h} [-(\bar{c}_A \eta_A U + e_A \xi \Psi_A) - (\bar{c}_B \eta_B U + e_B \xi \Psi_B)] \\
&= -\rho' \omega^2 U, \\
\bar{\varepsilon}'_{11} \xi^2 \Phi + \frac{1}{2h} (\varepsilon_A \xi \Psi_A + \varepsilon_B \xi \Psi_B) &= q N, \\
-qi \omega N + i \xi (-q \bar{n} \mu_{11} i \xi \Phi + q N \mu_{11} \bar{E}_1 - q d_{11} i \xi N) &= 0. \quad (33)
\end{aligned}$$

Eq.(33) is a system of linear homogeneous equations for U , Ψ_A , Ψ_B , Φ and N . For nontrivial solutions the determinant of the coefficient matrix of Eq.(33) has to vanish, which gives the following frequency equation that determines the dispersion relations of the waves:

$$\begin{aligned}
\rho' \frac{\omega^2}{\xi^2} \xi 2h - \bar{c}'_{44} \xi 2h - \bar{c}_A \frac{\eta_A}{\xi} - \bar{c}_B \frac{\eta_B}{\xi} + \frac{e_A^2}{\varepsilon_A} + \frac{e_B^2}{\varepsilon_B} \\
= \frac{(e_A + e_B)^2}{\bar{\varepsilon}'_{11} \xi 2h + \varepsilon_A + \varepsilon_B + \frac{q \bar{n} \mu_{11} 2h}{d_{11} \xi + i(\bar{E}_1 \mu_{11} - \omega / \xi)}}. \quad (34)
\end{aligned}$$

Or, in terms of the wave speed v , Eq.(34) can be written as

$$\begin{aligned}
\bar{c}'_{44} \left(\frac{v^2}{v_T'^2} - 1 \right) \xi 2h - \bar{c}_A \sqrt{1 - \frac{v^2}{v_A^2}} - \bar{c}_B \sqrt{1 - \frac{v^2}{v_B^2}} + \frac{e_A^2}{\varepsilon_A} + \frac{e_B^2}{\varepsilon_B} \\
= \frac{(e_A + e_B)^2}{\bar{\varepsilon}'_{11} \xi 2h + \varepsilon_A + \varepsilon_B + \frac{q \bar{n} \mu_{11} 2h}{d_{11} \xi + i(\bar{E}_1 \mu_{11} - v)}}. \quad (35)
\end{aligned}$$

where

$$v_T'^2 = c'_{44} / \rho'. \quad (36)$$

We observe from Eq.(35) that:

(i) As a special case, when $h=0$, i.e., the semiconductor film does not exist, Eq.(35) reduces to the

equation that determines the speed of interface waves between two ceramic half-spaces (Maerfeld and Tournois, 1971);

(ii) Different from the interface waves (Maerfeld and Tournois, 1971) which are not dispersive, waves determined by Eq.(35) are dispersive due to the presence of the film which introduces a length parameter h into the problem;

(iii) If the two half-spaces are of the same ceramics with opposite poling directions, we have (Maerfeld and Tournois, 1971)

$$\bar{c}_B = \bar{c}_A = \bar{c}, \quad e_B = -e_A = -e, \quad \varepsilon_B = \varepsilon_A = \varepsilon. \quad (37)$$

Then Eq.(35) simplifies to

$$\frac{\bar{c}'_{44}}{\bar{c}} \left(\frac{v^2}{v_T'^2} - 1 \right) \xi h - \sqrt{1 - \frac{v^2}{v_T'^2}} + k^2 = 0, \quad (38)$$

where

$$v_T'^2 = \bar{c} / \rho, \quad k^2 = e^2 / (\varepsilon \bar{c}). \quad (39)$$

Eq.(38) represents a dispersive but nondissipative wave. In this case the electric fields produced by the two ceramic half-spaces cancel with each other in the semiconductor film. Hence there is no conduction and dissipation in the film.

(iv) If the two half-spaces are of the same ceramics with the same poling direction, Eq.(35) reduces to

$$\begin{aligned}
\frac{\bar{c}'_{44}}{\bar{c}} \left(\frac{v^2}{v_T'^2} - 1 \right) \xi h - \sqrt{1 - \frac{v^2}{v_T'^2}} + k^2 \\
= \frac{\bar{\varepsilon}'_{11} \xi h + 1 + \frac{q \bar{n} \mu_{11} h}{\varepsilon [d_{11} \xi + i(\bar{E}_1 \mu_{11} - v)]}}{k^2}. \quad (40)
\end{aligned}$$

The denominator of the right-hand side of Eq.(40) indicates that a complex wave speed may be expected and that the imaginary part of the complex wave speed may change its sign (wave amplification) when $\mu_{11} \bar{E}_1 - v$ changes its sign or

$$v = \omega / \xi = \mu_{11} \bar{E}_1, \quad (41)$$

i.e., the acoustic wave speed is equal to the carrier drift speed.

NUMERICAL RESULTS

For numerical results we consider Eq.(40). When semiconduction is small, Eq.(40) can be solved by an iteration or perturbation procedure. As the lowest (zero) order of approximation, we neglect the semi-conduction and denote the zero-order solution by $v_{(0)}$. Then from Eq.(40)

$$\frac{\bar{c}'_{44}}{\bar{c}} \left(\frac{v_{(0)}^2}{v_T^2} - 1 \right) \xi h - \sqrt{1 - \frac{v_{(0)}^2}{v_T^2}} + k^2 = \frac{k^2}{\frac{\bar{\epsilon}'_{11}}{\epsilon} \xi h + 1}, \quad (42)$$

which determines $v_{(0)}$. For the next order we substitute $v_{(0)}$ into the right-hand side of Eq.(40) and obtain the following equation for $v_{(1)}$

$$\frac{\bar{c}'_{44}}{\bar{c}} \left(\frac{v_{(1)}^2}{v_T^2} - 1 \right) \xi h - \sqrt{1 - \frac{v_{(1)}^2}{v_T^2}} + k^2 = \frac{k^2}{\frac{\bar{\epsilon}'_{11}}{\epsilon} \xi h + 1 + \frac{q\bar{n}\mu_{11}h}{\epsilon [d_{11}\xi + i(\bar{E}_1\mu_{11} - v_{(0)})]}} \quad (43)$$

which suggests a wave that is both dispersive and dissipative.

For the ceramic half-spaces consider PZT-5H with $\rho_0=7500 \text{ kg/m}^3$ and (Auld, 1973)

$$\begin{aligned} c_{11}=12.6, c_{33}=11.7, c_{44}=2.30, \\ c_{12}=7.95, c_{13}=8.41 \times 10^{10} \text{ N/m}^2, c_{66}=(c_{11}-c_{12})/2, \quad (44) \\ e_{15}=17.0, e_{31}=-6.5, e_{33}=23.3 \text{ C/m}^2, \\ \epsilon_{11}=1700\epsilon_0, \epsilon_{33}=1470\epsilon_0, \epsilon_0=8.854 \times 10^{-12} \text{ farads/m} \end{aligned}$$

For silicon with $\rho_0=2332 \text{ kg/m}^3$, we have (Hellwege and Hellege, 1979; Lide, 2001-2002)

$$\begin{aligned} c'_{11} = 16.57, c'_{44} = 7.956, c'_{12} = 6.39 \times 10^{10} \text{ N/m}^2, \\ \epsilon'_{11} = 11.8\epsilon_0. \end{aligned} \quad (45)$$

The mobility of electrons and holes of silicon at 300 °K are (Navon, 1986)

$$\mu_n = 1500, \mu_p = 480 \text{ cm}^2 / \text{V} - \text{sec}. \quad (46)$$

The diffusion constants can be determined from the

Einstein relation (Navon, 1986)

$$D = \frac{kT}{q_e} \mu, \quad (47)$$

where T is the absolute temperature, and k the Boltzmann constant. At room temperature $kT/q_e=0.026 \text{ V}$ (Navon, 1986) where $q_e=1.602 \times 10^{-19}$ coulomb is the electronic charge.

We plot the real parts of $v_{(0)}$ and $v_{(1)}$ versus ξ in Fig.3. The dimensionless wave number X and the dimensionless wave speed Y of different orders are defined by

$$X = \xi / \frac{\pi}{2h}, Y_{(0)} = v_{(0)} / v_T, Y_{(1)} = \text{Re}\{v_{(1)}\} / v_T \quad (48)$$

γ is a dimensionless number given by

$$\gamma = \mu_{11} \bar{E}_1 / v_T, \quad (49)$$

which may be considered as a normalized electric field. It represents the ratio of the electron drift velocity and the speed of the shear acoustic wave. Because of the use of the thin film equations for the semiconductor layer, our solutions are valid only when the wavelength is much larger than the film thickness ($X \ll 1$). It can be seen that semiconduction causes dispersion. This conduction induced dispersion varies with the dc biasing electric field.

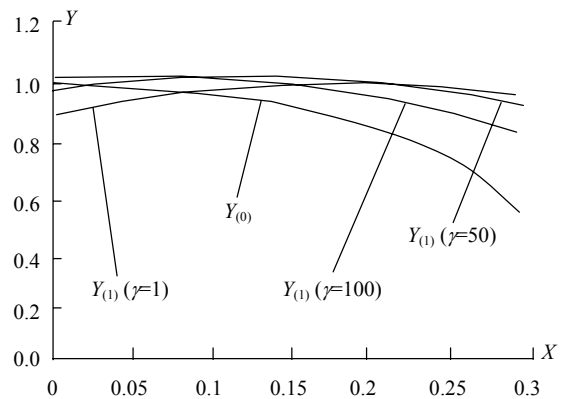


Fig.3 Dispersion relations

Fig.4 shows the imaginary part of $v_{(1)}$ versus $X=\gamma$. $\lambda=2\pi/\xi$ is the wave length. The dimensionless number describing the decaying behavior of the waves is defined by

$$Y = \text{Im}\{v_{(0)}\}/v_T. \quad (50)$$

When the dc bias is large enough (approximately $\gamma \gg 1$), the decay constant becomes negative indicating wave amplification. The transition from damped waves to growing waves indeed occurs when Eq.(41) is true for $v_{(0)}$. These agree qualitatively with the behavior of the 1-D plane waves (White, 1962).

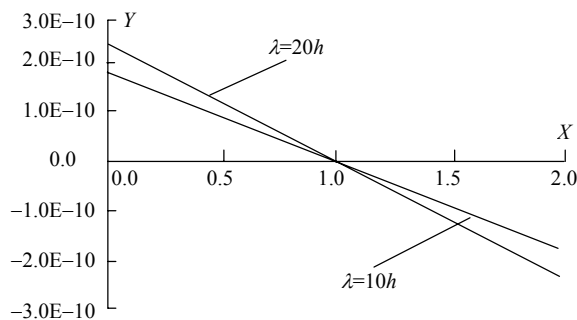


Fig.4 Dissipation as a function of the dc bias

CONCLUSION

Dispersion relations for anti-plane interface waves between two piezoelectric ceramic half-spaces with a semiconductor film are obtained. It is shown that semiconduction causes dispersion and acoustic loss in these waves. Acoustoelectric amplification occurs when the electron drift speed under a dc bias is larger than the shear acoustic wave speed. The equations for thin films simplify the analysis.

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