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Research Article

Modelling Reflection and Transmission of Acoustic Waves at a Semiconductor: Fluid Interface

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The paper concentrates on the study of reflection and transmission characteristics of acoustic waves at the interface of a semiconductor half-space underlying an inviscid liquid. The reflection and transmission coefficients varying with the incident angles are examined. Calculated results are verified by considering the quasilongitudinal (qP) and quasitransverse (qSV) waves. The special cases of normal and grazing incidence are also derived and discussed. Finally, the numerical computations of reflection and transmission coefficients are carried out with the help of Gauss elimination method by using MATLAB programming software for silicon (Si) and germanium (Ge) semiconductors. The computer simulated-results have been plotted graphically for Si and presented in tabular form in case of Ge semiconductors. The study may be useful in semiconductors, geology, and seismology in addition to surface acoustic wave (SAW) devices.

1. Introduction

Jeffrey's [1] and Gutenberg [2] considered the reflection of elastic plane waves at the surface of a solid halfspace. Sidhu and Singh [3] investigated the propagation of plane waves in a prestressed elastic solid possessing orthotropic symmetry and showed that the velocities of qL and qSV waves depend upon the angle of propagation. Rayleigh [4] considered the reflection and transmission of waves from an undulated boundary surface of an elastic solid. Knott [5] derived the equations for reflection and refraction of waves at plane boundaries. The reflection and refraction phenomenon of elastic waves in solids under different situations has been treated in detail as reported in books [6–8]. Deresiewicz [9] studied the reflection of a plane waves from the stress-free boundaries of thermoelastic halfspace. Abo-dahab [10] studied the propagation of P waves from the stress-free surface of elastic half-space with voids under the influence of thermal relaxation and magnetic field. It is found that the angle of incidence (θ) significantly affects the reflection coefficients and the thermal relaxation time has negligible small effect on the amplitude of reflection coefficients. Madeo and Gavrilyuk [11] studied the propagation of acoustic waves in porous media including their reflection and transmission at pure fluid/porous medium permeable interface. A. N. Sinha and S. B. Sinha [12] studied the reflection of generalized thermoelastic waves from the free surface of a solid halfspace. Sharma et al. [13] studied the reflection of generalized thermoelastic waves from the boundary of a transversely isotropic halfspace. Abd-alla [14] considered the effect of relaxation time on reflection of generalized magnetothermoelastic waves. Lockett [15] studied the effect of thermal properties of a solid on the velocity of waves. Chadwick and Snedon [16] studied the reflection of plane waves in an elastic solid conducting heat.

Maruszewski [17] presented theoretical considerations of the simultaneous interactions of elastic, thermal, and diffusion of charge carrier fields in order to study surface waves in semiconductors. Sharma and Thakur [18] non-dimensionalized the model [17] and studied the plane harmonic elastodiffusive surface wave in semiconductor material. Recently, J. N. Sharma and A. Sharma [19] studied the reflection of acoustodiffusive waves from the stress-free boundary of a semiconductor halfspace. As per knowledge of authors no study of reflection and transmission of waves based on the models of basic governing equations

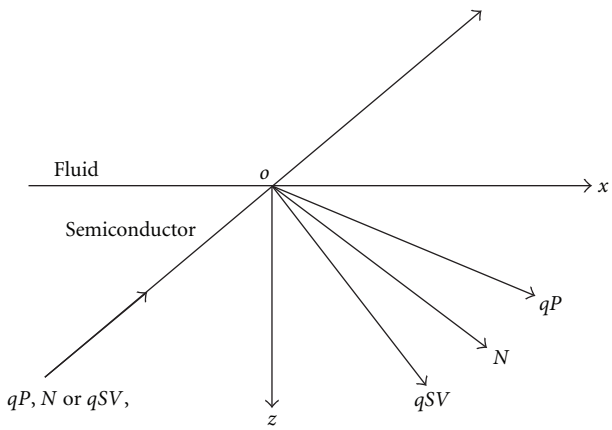

Figure 1: Geometry of the problem.

given in references [17, 18] is available in the literature. Ultrasonic waves are reflected at boundaries due to the acoustic impedance mismatch of the materials on each side. Reflection and transmission coefficients are utilized for the conversion of longitudinal to shear waves and vice versa. This feature is extremely useful in the construction of shear wave transducers. Reflection coefficients also affect the response of a transducer to a sinusoidal signal and are useful in sonography as well as in signal processing.

Keeping in view the above and applications of semiconductors in acoustic devices, the present paper is an attempt to explore the reflection and transmission characteristics of elastic waves at the interface between elastic semiconductor (n or p-type) halfspace and inviscid liquid semispace. The mathematical model consisting of governing partial differential equations of motion and charge carriers' diffusion of n-type and p-type semiconductors has been solved both analytically and numerically in the study. The computer-simulated results so obtained with the help of MATLAB programming in respect of in case of silicon (Si) and germanium (Ge) semiconductors in contact with water have been illustrated graphically.

2. Formulation of the Problem

We take the origin of rectangular Cartesian coordinate system $oxyz$ at a fixed point on the boundary of the semiconductor halfspace with positive z-axis directed normally into the solid medium and x-axis along the direction of propagation of waves; the y-axis is taken in the direction of the line of intersection of the plane wave front with the plane surface as shown in Figure 1. If we restrict our analysis to plain strain in the xz-plane, all the field variables may be taken as function of x, z, and t only. The basic governing equations of motion and diffusion of charge carrier fields for a homogeneous isotropic, elastic (n-type and p-type) semiconductors, in the absence of body forces and electromagnetic forces, are given as [17, 18].

n-type semiconductor

$$\begin{aligned} &\mu\nabla^2\vec{u} + (\lambda+\mu)\nabla\nabla\cdot\vec{u} - \lambda^n N = \rho\ddot{\vec{u}}, \\ &\rho D^n\nabla^2 N + \rho\left[\frac{1}{t_n^+} - \left(1 - \frac{t^n}{t_n^+}\right)\frac{\partial}{\partial t} - t^n\frac{\partial^2}{\partial t^2}\right]N \\ &\quad - a_2^n T_0\lambda^T\nabla\cdot\dot{\vec{u}} = 0, \end{aligned} \tag{1}$$

p-type semiconductor

$$\begin{aligned} &\mu\nabla^2\vec{u} + (\lambda+\mu)\nabla\nabla\cdot\vec{u} - \lambda^p P = \rho\ddot{\vec{u}}, \\ &\rho D^p\nabla^2 P + \rho\left[\frac{1}{t_p^+} - \left(1 - \frac{t^p}{t_p^+}\right)\frac{\partial}{\partial t} - t^p\frac{\partial^2}{\partial t^2}\right]P \\ &\quad - a_2^p T_0\lambda^T\nabla\cdot\dot{\vec{u}} = 0, \end{aligned} \tag{2}$$

where $\nabla^2 = (\partial^2/\partial x^2) + (\partial^2/\partial z^2)$ is the Laplacian operator, $N(x,z,t) = n - n_0$ is the electron concentration change, $P(x,z,t) = p - p_0$ is the hole concentration change, and $\vec{u}(x,z,t) = (u,0,w)$ is the displacement vector. Here λ, μ are Lame parameters; ρ is the density of the semiconductor; $\lambda^n = (3\lambda+2\mu)\alpha_N$ and $\lambda^p = (3\lambda+2\mu)\alpha_P$ are the elastodiffusive constants of electrons; α_N, α_P are the coefficients of linear electron and holes concentration expansions. D^n and D^p are the diffusion coefficients of electron and hole carriers; t_n, t_p and t_n^+, t_p^+ are the relaxation and life times of the electron and hole charge carriers, respectively; n, p and n_0, p_0 are, respectively, the nonequilibrium and equilibrium values of electrons and holes concentrations of the semiconductors; T_0 and $\lambda^T = (3\lambda + 2\mu)\alpha_T$ are the uniform temperature and adiabatic thermomechanical coupling constant, respectively; a_2^n, a_2^p are the flux-like parameters. The superposed dot represents differentiation with respect to time.

Further (1)-(2) are subjected to following assumptions [17, 18].

(i) All the considerations are made in the frame work of the phenomenological model.

(ii) The electric neutrality of the semiconductor is satisfied.

(iii) The magnetic field effect is ignored.

(iv) The mass of charge carriers is negligible.

(v) The electric field with in the boundary layer is very weak and can be neglected.

(vi) The recombination functions of electrons and holes are selected on the basis of facts that take care of the defects and hence the concentration values of the charge carrier fields.

The nonvanishing components of stress tensor in the semiconductor are given by

n-type:

$$\tau_{zz} = (\lambda+2\mu)\frac{\partial w}{\partial z} + \lambda\frac{\partial u}{\partial x} - \lambda^n N, \qquad \tau_{xz} = \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right), \tag{3}$$

p- type:

$$\tau_{zz} = (\lambda + 2\mu)\frac{\partial w}{\partial z} + \lambda\frac{\partial u}{\partial x} - \lambda^p P, \qquad \tau_{xz} = \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right). \tag{4}$$

The basic governing equation for inviscid fluid medium is given by

$$\lambda_L \nabla\nabla\cdot\vec{u}_L = \rho_L \ddot{\vec{u}}, \tag{5}$$

where λ_L is bulk modulus and ρ_L and $\vec{u}_L$ are the density of the fluid and velocity vector, respectively.

We define the quantities

$$\begin{gathered} x' = \frac{\omega^* x}{c_1}, \qquad z' = \frac{\omega^* z}{c_1}, \qquad t' = \omega^* t, \\ N' = \frac{N}{n_0}, \qquad w' = \frac{\rho\omega^* c_1}{\lambda^n n_0} w, \qquad u' = \frac{\rho\omega^* c_1}{\lambda^n n_0} u, \\ \tau'_{ij} = \frac{\tau_{ij}}{\lambda^n n_0}, \qquad t^{n\prime} = t^n\omega^*, \qquad t_n^{+\prime} = t_n^+\omega^*, \\ \delta_L^2 = \frac{c_L^2}{c_1^2}, \qquad c_L^2 = \frac{\lambda_L}{\rho_L}, \qquad \delta^2 = \frac{c_2^2}{c_1^2}, \\ \omega^* = \frac{c_1^2}{D^n}, \qquad c_1^2 = \frac{\lambda + 2\mu}{\rho}, \qquad c_2^2 = \frac{\mu}{\rho}, \end{gathered} \tag{6}$$

$$\varepsilon_n = \frac{a_2^n T_0 \lambda^T \lambda^n}{\rho(\lambda + 2\mu)}, \qquad u'_L = \frac{\rho\,\omega^* c_1}{\lambda^n n_0} u_L, \tag{7}$$

where ω^* is the elastodiffusive characteristic frequency and c_1, c_2 are, respectively, the longitudinal and shear wave velocities. Here ε_L is the thermomechanical coupling and c_L is the velocity of sound in the fluid. Such quantities in case of p-type semiconductor can be written from those in (6) by replacing the subscript/superscripts n with p and the quantity N with P. Upon using quantities (6) in (1)–(4), and (5), we obtain (n-type semiconductor)

$$\delta^2\nabla^2\vec{u} + (1-\delta^2)\nabla\nabla\cdot\vec{u} - \nabla N = \ddot{\vec{u}}, \tag{8}$$

$$\nabla^2 N - \left[t^n\frac{\partial^2}{\partial t^2} + \left(1 - \frac{t^n}{t_n^+}\right)\frac{\partial}{\partial t} - \frac{1}{t_n^+}\right]N - \varepsilon_n\nabla\cdot\dot{\vec{u}} = 0, \tag{9}$$

$$\tau_{xz} = \delta^2\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right), \qquad \tau_{zz} = (1 - 2\delta^2)\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} - N, \tag{10}$$

$$\delta_L^2\nabla\nabla\cdot\vec{u}_L = \ddot{\vec{u}}_L. \tag{11}$$

The equations for p-type semiconductor can be written from (8) and (9) by replacing N with P and superscripts/subscripts n with p.

We introduce the elastic potential functions ϕ and ψ through the relations

$$u = \frac{\partial\phi}{\partial x} + \frac{\partial\psi}{\partial z}, \qquad w = \frac{\partial\phi}{\partial z} - \frac{\partial\psi}{\partial x}. \tag{12}$$

However, in general, such a decomposition of displacement vector is not possible in case of anisotropic materials [3].

Upon introducing (11) in (8) and (9), we get

$$\nabla^2\phi - \ddot{\phi} - N = 0, \tag{13}$$

$$\nabla^2 N - \left[t^n\frac{\partial^2}{\partial t^2} + \left(1 - \frac{t^n}{t_n^+}\right)\frac{\partial}{\partial t} - \frac{1}{t_n^+}\right]N - \varepsilon_n\nabla^2\dot{\phi} = 0, \tag{14}$$

$$\nabla^2\psi = \frac{\ddot{\psi}}{\delta^2}. \tag{15}$$

Similarly for p-type semiconductor, we have

$$\nabla^2\phi - \ddot{\phi} - P = 0, \tag{16}$$

$$\nabla^2 P - \left[t^p\frac{\partial^2}{\partial t^2} + \left(1 - \frac{t^p}{t_p^+}\right)\frac{\partial}{\partial t} - \frac{1}{t_p^+}\right]P - \varepsilon_p\nabla^2\dot{\phi} = 0, \tag{17}$$

$$\nabla^2\psi = \frac{\ddot{\psi}}{\delta^2}. \tag{18}$$

In case the semiconductors are of relaxation type, the life time and relaxation time become comparable to each other ($t^n \cong t_n^+$), and consequently, (14) get simplified. The stresses (10) in terms of potential functions ϕ and ψ with the help of (12) to (18) become

$$\tau_{zz} = \ddot{\phi} - 2\delta^2(\phi_{,xx} + \psi_{,xz}), \qquad \tau_{xz} = \ddot{\psi} + 2\delta^2(\phi_{,xz} - \psi_{,xx}) \tag{19}$$

for both n-type and p-type semiconductors. In the fluid medium, the nondimensional displacements are related to scalar and vector velocity potential through the relations given by

$$u_L = \phi_{L,x}, \qquad w_L = \phi_{L,z}. \tag{20}$$

Substituting (20) in (12) we get

$$\delta^2\nabla^2\phi_L - \ddot{\phi}_L = 0. \tag{21}$$

This is the equation for waves in the inviscid fluid.

3. Boundary Conditions

Following sets of boundary conditions are assumed to hold at solid-fluid interface $z = 0$ of the semiconductor halfspace [20].

(1) The magnitude of the normal component of stress tensor of the elastic half-space should be equal to the pressure of the liquid. This implies that

$$\frac{\ddot{\phi}}{\delta^2} - 2(\phi_{,xx} + \psi_{,xz}) = \frac{\rho_L\ddot{\phi}_L}{\rho\delta^2}. \tag{22}$$

(2) The tangential components of stress tensor of the solid should be zero, which implies that

$$\frac{\ddot{\psi}}{\delta^2} - 2(\psi_{,xx} - \phi_{,xz}) = 0. \tag{23}$$

(3) The normal component of displacement of the solid should be equal to that of fluid, which implies that

$$\phi_{,z} - \psi_{,x} = \phi_{L,z}. \tag{24}$$

(4) The electron and hole charge carrier fields satisfy the following conditions at the interface $z = 0$

$$\begin{aligned} \frac{\partial N}{\partial z} + h_n\left(1 + t^n \frac{\partial}{\partial t}\right)N = 0, \\ \frac{\partial P}{\partial z} + h_p\left(1 + t^p \frac{\partial}{\partial t}\right)P = 0, \end{aligned} \tag{25}$$

where $h_n = s^n/c_1$, $h_p = s^p/c_1$, s^n and s^p surface recombination velocities of electron and holes, respectively.

4. Reflection and Transmission of Plane Waves

We assume plane wave solution of the form

$$\begin{aligned} (\phi, \psi, N, P, \phi_L) = (A, B, C, D, E) \\ \times \exp\{\iota k(x \sin\theta - z\cos\theta - vt)\}, \end{aligned} \tag{26}$$

where $v = \omega/k$, ω is circular frequency, and k is the wave number. Upon using (26) in (13)–(18) and in (21) we obtain a system of algebraic equations in unknowns A, B, C, D. The condition for the existence of nontrivial solution of these systems of equations provides us

n-type:

$$k_1^2 = a_1^2\omega^2, \quad k_2^2 = a_2^2\omega^2, \quad k_3^2 = \frac{\omega^2}{\delta^2}, \quad k_4^2 = a_4^2\omega^2, \tag{27}$$

p-type:

$$k_1^{*2} = a^{*2}{}_1\omega^2, \quad k_2^{*2} = a_2^{*2}\omega^2, \quad k_3^{*2} = \frac{\omega^2}{\delta^2}, \quad k_4^{*2} = a_4^{*2}\omega^2, \tag{28}$$

where

$$\begin{gathered} a_1^2 + a_2^2 = 1 + \alpha_n^* + \iota\omega^{-1}\varepsilon_n, \\ a_1^2 a_2^2 = \alpha_n^*, \quad a_3^2 = \frac{1}{\delta^2}, \quad a_4^2 = \frac{1}{\delta_L^2}, \\ a_1^{*2} + a_2^{*2} = 1 + \alpha_p^* + \iota\omega^{-1}\varepsilon_p, \quad a_1^2 a_2^2 = \alpha_p^*. \end{gathered} \tag{29}$$

5. Reflection and Transmission in Case of qP Wave Incidence

Let the suffixes i and r represent incident and reflected waves, respectively. Omitting the term $\exp(-\iota\omega t)$, the solution (26) for the function ϕ, ψ, N, ϕ_L and P in case of incidence and reflected waves can be written as

$$\begin{aligned} \phi_i &= A_i \exp\{ik_1(x\sin\theta_1 - z\cos\theta_1)\}, \\ \phi_r &= \sum_{j=1}^{2} A_j \exp\left\{ik_j\left(x\sin\theta_j + z\cos\theta_j\right)\right\}, \\ \psi_r &= A_3 \exp\{ik_3\ (x\sin\theta_3 + z\cos\theta_3)\}, \\ N_i &= S_1 A_i \exp\{\iota k_1(x\sin\theta - z\cos\theta)\}, \\ N_r &= \sum_{j=1}^{2} S_j A_j \exp\left\{\iota k_j\left(x\sin\theta_j + z\cos\theta_j\right)\right\}, \\ P_i &= S_1^* A_i \exp\{\iota k_1^*(x\sin\theta - z\cos\theta)\}, \\ P_r &= \sum_{j=1}^{2} S_j^* A_j \exp\left\{\iota k_j^*\left(x\sin\theta_j + z\cos\theta_j\right)\right\}, \end{aligned} \tag{30}$$

where

$$\begin{aligned} S_j &= \omega^2 - k_j^2 = \omega^2\left(1 - a_j^2\right), \quad j = 1, 2, \\ S_j^* &= \omega^2 - k_j^{*2} = \omega^2\left(1 - a_j^{*2}\right), \quad j = 1, 2. \end{aligned} \tag{31}$$

In the absence of electron field ($N = 0 = \varepsilon_n$) and hole carriers ($P = 0 = \varepsilon_p$), we have

$$\begin{aligned} &\text{n-type: } a_1^2 = 1,\ a_2^2 = \alpha_n^*,\ a_3^2 = \frac{1}{\delta^2},\ a_4^2 = \frac{1}{\delta_L^2}, \\ &\text{p-type: } a_1^{*2} = 1,\ a_2^{*2} = \alpha_p^*, \\ &S_1 = 0, \qquad S_2 = \omega^2(1 - \alpha_n^*), \\ &S_1^* = 0, \qquad S_2^* = \omega^2\left(1 - \alpha_p^*\right). \end{aligned} \tag{32}$$

Case 1 (Quasilongitudinal (qP) wave incidence at an interface from the semiconductor). In this and the following sections, we shall confine our discussion to n-type semiconductor unless stated otherwise, and results in case of p-type semiconductor can be written from the expressions of various quantities obtained here by adopting the same procedure.

Because of coupling between various field functions the reflected fields in case of qP wave incidence at the interface are given by

$$\begin{gathered} \phi = \phi_i + \phi_r, \qquad N = N_i + N_r, \qquad P = P_i + P_r, \\ \psi = \psi_r, \qquad \phi_L = \phi_{Lr}. \end{gathered} \tag{33}$$

Upon using the above equations, we calculate the stresses from (19) and then employing the boundary conditions (22)–(25) to obtain a system of four coupled algebraic equations given in the appendix. Since all the waves, incident, reflected, or transmitted, must be in phase at the surface $z = 0$ for all values of x and t, therefore from equations (A.1) we have

$$k_1 \sin\theta = k_1 \sin\theta_1 = k_2 \sin\theta_2 = k_3 \sin\theta_3 = k_4 \sin\theta_4. \tag{34}$$

Upon using (27) in the above relation, we obtain

$$\theta = \theta_1, \qquad a_1 \sin\theta_1 = a_2 \sin\theta_2 = \frac{1}{\delta}\sin\theta_3 = a_4 \sin\theta_4. \tag{35}$$

This is modified form of the Snell's law for the considered material. In the absence of electron field ($N = 0$, $\varepsilon_n = 0$), (35) becomes

$$\delta \sin\theta_1 = \sin\theta_3 \Longrightarrow \frac{\sin\theta_1}{c_1} = \frac{\sin\theta_3}{c_2}. \tag{36}$$

This is Snell's law [6]. Solving the systems of equations (A.2) with the help of Gauss elimination method, the amplitude ratios R_k^{qP} $(k = 1, 2, 3)$ and T_1^{qP} are obtained as

$$\begin{aligned}
R_1^{qP} &= 1 - \frac{2a_2S_2\cos\theta_2\cos^2 2\theta_3}{\overline{a}\Delta_L - \Delta_S},\\
R_2^{qP} &= \frac{-2S_1a_1a_4\delta\cos\theta_4\cos\theta_1\cos^2 2\theta_3}{\overline{\rho}\Delta_L - a_4\delta\cos\theta_4\Delta_S}\\
&= \frac{-2S_1a_1\cos\theta_1\cos^2 2\theta_3}{\overline{a}\Delta_L - \Delta_S},\\
R_3^{qP} &= \frac{2a_1a_2\delta^2(a_1S_2\sin 2\theta_1\cos\theta_2 - a_2S_1\cos\theta_1\sin 2\theta_2)\cos 2\theta_3}{\overline{a}\Delta_L - \Delta_S},
\end{aligned} \tag{37}$$

$$\begin{aligned}
T_1^{qP} &= \frac{2a_1a_2\cos\theta_1\cos\theta_2\cos^2 2\theta_3(S_2 - S_1)}{a_4\cos\theta_4(\overline{a}\Delta_L - \Delta_S)}\\
&\quad + \frac{a_1a_2\delta\sin 2\theta_3(a_1S_2\cos\theta_2\sin 2\theta_1 - a_2S_1\cos\theta_1\sin 2\theta_2)}{a_4\cos\theta_4(\overline{a}\Delta_L - \Delta_S)},
\end{aligned} \tag{38}$$

where

$$\overline{a} = \frac{\overline{\rho}}{a_4\delta\cos\theta_4}, \tag{39}$$

$$\begin{aligned}
\Delta_L &= \cos\theta_1\cos\theta_2\cos 2\theta_3 a_1a_2\delta(S_2 - S_1)\\
&\quad + a_1a_2\delta^2(a_1S_2\sin 2\theta_1\cos\theta_2 - a_2S_1\sin 2\theta_2\cos\theta_1)\sin\theta_3,
\end{aligned} \tag{40}$$

$$\begin{aligned}
\Delta_S &= [a_1S_1\cos\theta_1[\cos^2 2\theta_3 + a_2^2\delta^2\sin 2\theta_2\sin 2\theta_3]\\
&\quad - a_2S_2\cos\theta_2[\cos^2 2\theta_3 + a_1^2\delta^2\sin 2\theta_1\sin 2\theta_3]].
\end{aligned} \tag{41}$$

In the absence of fluid medium (37) becomes

$$\begin{aligned}
R_1^{qP} &= \frac{a_1S_1\cos\theta_1[\cos^2 2\theta_3 + a_2^2\delta^2\sin 2\theta_2\sin 2\theta_3]}{\Delta_S}\\
&\quad + \frac{a_2S_2\cos\theta_2[\cos^2 2\theta_3 - a_1^2\delta^2\sin 2\theta_1\sin 2\theta_3]}{\Delta_S},\\
R_2^{qP} &= \frac{-2a_1S_1\cos^2 2\theta_3\cos\theta_1}{\Delta_S},\\
R_3^{qP} &= \frac{2a_1^2a_2\delta^2\cos 2\theta_3[a_2S_1\sin 2\theta_2\cos\theta_1 - a_1S_2\cos\theta_2\sin 2\theta_1]}{\Delta_S}.
\end{aligned} \tag{42}$$

In the absence of fluid medium and electron field ($N = 0$, $\varepsilon_n = 0$), the expression (37) and (42) for amplitude ratios with the help of (32) becomes

$$\begin{aligned}
R_1^{qP} &= \frac{\delta^2\sin 2\theta_1\sin 2\theta_3 - \cos^2 2\theta_3}{\delta^2\sin 2\theta_1\sin 2\theta_3 + \cos^2 2\theta_3},\\
R_2^{qP} &= 0,\\
R_3^{qP} &= \frac{2\,\delta^2\sin 2\theta_1\cos 2\theta_3}{\delta^2\sin 2\theta_1\sin 2\theta_3 + \cos^2 2\theta_3}.
\end{aligned} \tag{43}$$

These relations are in complete agreement with the corresponding equations as given by Achenbach [6] in case of elastokinetics. In case of grazing incidence, ($\theta = 90^\circ = \theta_1$) the amplitude ratios given by (37)-(39) with the use of Snell's law provide us

$$R_1^{qP} = -1, \qquad R_2^{qP} = 0, \qquad R_3^{qP} = 0. \tag{44}$$

This shows that qSV wave and electron waves are not reflected and qP wave annihilates itself being 180° out of phase with the incident wave. Similarly for normal incidence ($\theta = 0^\circ = \theta_1$), the corresponding values of reflection coefficients from (37)–(42) are again obtained as

$$R_1^{qP} = -1, \quad R_2^{qP} = 0, \quad R_3^{qP} = 0 = T_1^{qP}. \tag{45}$$

Here qP wave gets reflected and transmitted in case of normal incidence.

Case 2 (*Quasitransverse* (qSV) *wave incidence at an interface from semiconductor*). We now consider the reflection of a plane qSV wave for similar conditions on the boundary as in the previous section. For qSV wave, we have

$$\begin{aligned}
\psi &= \psi_i + \psi_r\\
&= A_i\exp\{\iota k_3(x\sin\theta - z\cos\theta)\}\\
&\quad + A_3\exp\{\iota k_3(x\sin\theta_3 + z\cos\theta_3)\},\\
\phi &= \phi_r = \sum_{r=1}^{2} A_r\exp\{\iota k_r(x\sin\theta_r + z\cos\theta_r)\},\\
N &= N_r = \sum_{r=1}^{2} S_rA_r\exp\{\iota k_r(x\sin\theta_r + z\cos\theta_r)\},\\
\phi_L &= A_4\exp\{\iota k_4(x\sin\theta_4 - z\cos\theta_4)\}.
\end{aligned} \tag{46}$$

Upon using solution (46) in the boundary conditions (22) and (25) at the surface $z = 0$ and assuming that all the incident or reflected waves are in phase at this surface for all values of x and t, we have the relation

$$k_3\sin\theta = k_1\sin\theta_1 = k_2\sin\theta_2 = k_3\sin\theta_3. \tag{47}$$

This relation implies that

$$\theta = \theta_3, \qquad a_1\sin\theta_1 = a_2\sin\theta_2 = \frac{1}{\delta}\sin\theta_3. \tag{48}$$

This is the modified form of Snell's law for the considered material, in this case. Upon solving (A.4) and (A.5), we get

$$\begin{aligned}
R_1^{qSV} &= \frac{-S_2\ a_2\cos\theta_2\sin 4\theta_3}{\overline{a}\Delta_L - \Delta_S},\\
R_2^{qSV} &= \frac{a_1S_1\cos\theta_1\sin 4\theta_3}{\overline{a}\Delta_L - \Delta_S},\\
R_3^{qSV} &= \frac{\mathfrak{R}}{(\overline{a}\Delta_L - \Delta_S)},\\
T_1^{qSV} &= \frac{2\sin 2\theta_3\Delta_L}{\overline{\rho}\Delta_L - a_4\delta\cos\theta_4\Delta_S}.
\end{aligned} \tag{49}$$

where $\mathfrak{R}$ denotes $\{\overline{a}\Delta_L - \{a_1a_2\delta^2(a_2S_1\cos\theta_1\sin 2\theta_2 - a_1S_2\cos\theta_2\sin 2\theta_1)\times\sin 2\theta_3 - (a_1S_1\cos\theta_1 - a_2S_2\cos\theta_2)\cos^2 2\theta_3\}\}$.

Here Δ_L and Δ_S are defined in (40) and (41), respectively. In the absence of fluid medium (49) becomes

$$\begin{aligned} R_1^{qSV} &= \frac{S_2 a_2 \cos\theta_2 \sin 4\theta_3}{\Delta_S}, \\ R_2^{qSV} &= \frac{-a_1 S_1 \cos\theta_1 \sin 4\theta_3}{\Delta_S}, \\ R_3^{qSV} &= \frac{\mathcal{R}}{\Delta_S}, \end{aligned} \tag{50}$$

where Δ_S is defined by (41). In the absence of fluid medium and electron field ($\varepsilon_n = 0 = N$), (49) and (50) reduce to

$$\begin{aligned} R_1^{qSV} &= \frac{-\sin 4\theta_3}{\cos^2 2\theta_3 + \delta^2 \sin 2\theta_1 \sin 2\theta_3}, \\ R_2^{qSV} &= 0, \\ R_3^{qSV} &= \frac{\delta^2 \sin 2\theta_3 \sin 2\theta_1 - \cos^2 2\theta_3}{\cos^2 2\theta_3 + \delta^2 \sin 2\theta_3 \sin 2\theta_1}, \end{aligned} \tag{51}$$

Equations (51) agree with the corresponding equations in Achenbach [6] and Kino [7]. For grazing incidence ($\theta = 90^\circ = \theta_3$) and in case of normal incidence ($\theta = 0^\circ = \theta_3$), the expressions for reflection coefficients in (49)–(51) provide us

$$R_1^{qSV} = 0, \quad R_2^{qSV} = 0, \quad T_1^{qSV} = 0, \quad R_3^{qSV} = -1. \tag{52}$$

Therefore, only shear wave is reflected as qSV wave in case of normal incidence, and the reflected qSV wave annihilates the incident qSV wave in case of grazing incidence case. The other two waves, namely, qP and N, are not reflected, and there is no transmitted wave in either case of normal or grazing incidence.

6. Energy Equations

From the principle of conservation of energy, the energy carried to the boundary by the incident wave must be equal to the energy carried away from the boundary by the reflected and refracted waves. For the incident qSV wave incidence the particle velocities are

$$\begin{aligned} \overline{v} &= \frac{\partial^2 \psi_i}{\partial x \partial t} \\ &= \omega k_3 \sin\theta A_i \exp\{\imath k_3 (x \sin\theta - z\cos\theta - vt)\}, \\ \varpi &= \frac{\partial^2 \psi_i}{\partial z \partial t} \\ &= -\omega k_3 \cos\theta_3 A_i \exp\{i k_3 (x \sin\theta - z\cos\theta - vt)\}. \end{aligned} \tag{53}$$

For reflected qSV waves,

$$\begin{aligned} \overline{v} &= \frac{\partial^2 \psi_r}{\partial x \partial t} \\ &= \omega k_3 \sin\theta_3 A_3 \exp\{i k_3 (x \sin\theta_3 + z\cos\theta_3 - vt)\}, \\ \varpi &= \frac{\partial^2 \psi_r}{\partial z \partial t} \\ &= \omega k_3 \cos\theta_3 A_3 \exp\{i k_3 (x \sin\theta_3 + z\cos\theta_3 - vt)\}. \end{aligned} \tag{54}$$

For reflected qP waves,

$$\begin{aligned} \overline{v} &= \frac{\partial^2 \phi_r}{\partial x \partial t} \\ &= \omega k_1 \sin\theta_1 A_1 \exp\{i k_1 (x \sin\theta_1 + z\cos\theta_1 - vt)\} \\ &\quad + \omega k_2 \sin\theta_2 A_2 \exp\{i k_2 (x \sin\theta_2 + z\cos\theta_2 - vt)\}, \\ \varpi &= \frac{\partial^2 \phi_r}{\partial z \partial t} \\ &= \omega k_1 \cos\theta_1 A_1 \exp\{i k_1 (x \sin\theta_1 + z\cos\theta_1 - vt)\} \\ &\quad + \omega k_2 \cos\theta_2 A_2 \exp\{i k_2 (x \sin\theta_2 + z\cos\theta_2 - vt)\}. \end{aligned} \tag{55}$$

For transmitted qP waves,

$$\begin{aligned} \overline{v} &= \frac{\partial^2 \phi_{Lr}}{\partial x \partial t} \\ &= \omega k_4 \sin\theta_4 A_4 \exp\{i k_4 (x \sin\theta_4 - z\cos\theta_4 - vt)\}, \\ \varpi &= \frac{\partial^2 \phi_{Lr}}{\partial z \partial t} \\ &= -\omega k_4 \cos\theta_4 A_4 \exp\{i k_4 (x \sin\theta_4 - z\cos\theta_4 - vt)\}. \end{aligned} \tag{56}$$

Taking the kinetic energy per unit volume as $(1/2)\rho(\overline{v}^2 + \varpi^2)$, we may calculate the energy flux for the waves mentioned above by multiplying the total energy per unit volume by the velocity of propagation and area of the wave front involved. Thus we may write the equality between the incident qSV wave energy and the sum of reflected qP, reflected qSV, and transmitted qSV-wave energies for the per unit area on the interface as

$$\begin{aligned} c_2 \cos\theta_3 k_3^2 &= c_1 \cos\theta_2 k_1^2 R_1^2 + c_1 \cos\theta_2 k_2^2 R_2^2 \\ &\quad + c_2 \cos\theta_2 k_3^2 R_3^2 + \frac{\rho_L}{\rho} c_L \cos\theta_4 k_4^2 R_4^2. \end{aligned} \tag{57}$$

Here the cross-sectional areas of the incident, reflected, and transmitted waves are proportional to the cosines of the angles made by the ray directions of the waves with the normal to the interface. Hence the energy equation is given by

$$1 \cong Z, \tag{58}$$

where

$$Z = \frac{c_2}{c_1} \frac{\cos\theta_2}{\cos\theta_3} R_1^2 + R_3^2 - \frac{c_2}{c_L} \frac{\rho_L}{\rho} \frac{\cos\theta_4}{\cos\theta_3} R_4^2. \tag{59}$$

7. (p-Type) Semiconductor

The reflection coefficients and transmission coefficients in case of p-type semiconductor can be obtained by using boundary conditions (22)–(25) and solution (26) for the functions ϕ, ψ, ϕ_L, and P by adopting the procedure of previous sections. The expressions of the reflection coefficients R_K^{qP} and R_K^{qSV} ($k = 1, 2, 3$) are again given by (37)–(42) and (49)–(51) in case of qP-wave, qSV-wave incident at the surface of p-type semiconductor, respectively, with the replacement of a_i^2 ($i = 1, 2$) as the a_i^{*2} ($i = 1, 2$) in all the relevant relations and equations including Snell's law.

Table 1: Physical data of Silicon (Si) and Germanium (Ge) semiconductors.

Coefficient	Unit	Value (Ge)	Value (Si)	Reference
λ	Nm^{-2}	0.48×10^{11}	0.64×10^{11}	[17]
μ	Nm^{-2}	0.53×10^{11}	0.65×10^{11}	
ρ	Kgm^{-3}	5.3×10^{3}	2.3×10^{3}	
t_n^+	s	1 ps	1 ps	
t_p^+	s	1 ps	1 ps	
D^n	$\mathrm{m}^2\,\mathrm{s}^{-1}$	10^{-2}	0.35×10^{-2}	
D^p	$\mathrm{m}^2\,\mathrm{s}^{-1}$	0.5×10^{-2}	0.125×10^{-2}	
α_T	K^{-1}	5.8×10^{-6}	2.6×10^{-6}	[21]
$n_0 = p_0$	m^{-3}	10^{20}	10^{20}	[22]

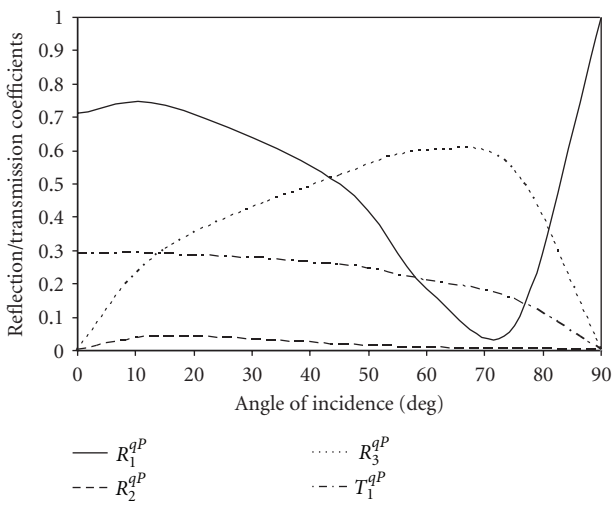

Figure 2: qP wave incidence at the interface of semiconductor and fluid.

8. Numerical Results and Discussion

In this section the reflection and transmission coefficients given by (37)–(39) and (49)-(50) have been computed numerically for silicon (Si) and germanium (Ge) materials under the assumption of relaxation type semiconductor (n-type or p-type) under the assumption that semiconductor considered is of relaxation type so that t_n, t_n^+ and t_p, t_p^+ become comparable to each other in their values such that $t_n = t_n^+$ and $t_p = t_p^+$.

Here the fluid chosen for the purpose of numerical calculations is water, the velocity of sound in which is given by $c_L = 1.5 \times 10^3$ m/s and density is $\rho_L = 1000\,\mathrm{kg/m^3}$.

The physical data for silicon material is given below in Table 1.

The values of reflection coefficients $R_k^{qP}(k = 1,2,3)$, $R_k^{qSV}(k = 1,2,3)$, and transmission coefficients T_1^{qP}, T_1^{qSV} for incident qP and qSV waves have been computed from (37)–(39) and (49)-(50) for various values of the angle of incidence (θ) lying between $0^\circ \le \theta \le 90^\circ$ for silicon (Si) semiconductor.

From Figure 2, it is noticed that the magnitude of reflection coefficient (R_1^{qP}) marginally increases in the range $0^\circ \le \theta \le 10^\circ$ with increase in angle of incidence and decreases in the range $10^\circ \le \theta \le 70^\circ$; that is, there is a sharp loss of energy which is noticed in the range $10^\circ \le \theta \le 70^\circ$ before it sharply increases upto $\theta = 90^\circ$ in case of qP wave incidence at the interface of semiconductor and fluid. The magnitude of reflection coefficient (R_3^{qP}) increases for $0^\circ \le \theta \le 60^\circ$ and attains a maximum value at $\theta = 75^\circ$; that is, loss of energy by reflected wave (R_1^{qP}) is covered by reflected wave (R_3^{qP}). However, a meager amount of energy is associated with an electron wave (R_2^{qP}). It is also noticed that transmission coefficient T_1^{qP} attains a maximum value at $\theta = 0^\circ$ and then varies linearly up to $0^\circ \le \theta \le 15^\circ$; after that it starts decreasing up to $\theta = 90^\circ$. This implies that in case of qP wave incidence at the interface of semiconductor and fluid, transmitted wave also travels with sufficient amount of energy. It is revealed that at grazing incidence $\theta = 90^\circ$, the reflection coefficients $R_k^{qP}(k = 1,2,3)$ and transmission coefficient T_1^{qP} of incident qP wave vanish, thereby meaning that reflected qP wave annihilates the incident qP wave. Whereas in contrast to this qP wave is reflected and transmitted as qP wave at normal incidence ($\theta = 0^\circ$), and other waves are not reflected or transmitted. Thus maximum energy is carried by longitudinal (qP) waves, reflected or transmitted, at normal and grazing incidence, though it is transported in a distributed manner among all coupled waves at other angles of incidence. The trend and nature of reflection/transmission coefficients in case of qP wave incidence in Figure 2 almost completely agree with those presented in Kino [7].

In Figure 3, it is noticed that reflection coefficient R_1^{qSV} increases with increase in angle of incidence in the range $0^\circ \le \theta \le 30^\circ$ and attains a maximum value at ($\theta = 30^\circ$) due to stresses generated in the semiconductor material; after that it starts decreasing up to $30^\circ \le \theta \le 45^\circ$. Thus shear wave incidence has a critical angle at $\theta = 45^\circ$. Beyond this cutoff point, the amplitude of longitudinal wave component at the surface is finite, but no real power is associated with them; only decaying fields are associated with them. However, the reflection coefficient R_2^{qSV} increases sharply and attains a maximum energy at $\theta = 30^\circ$, then decreases for

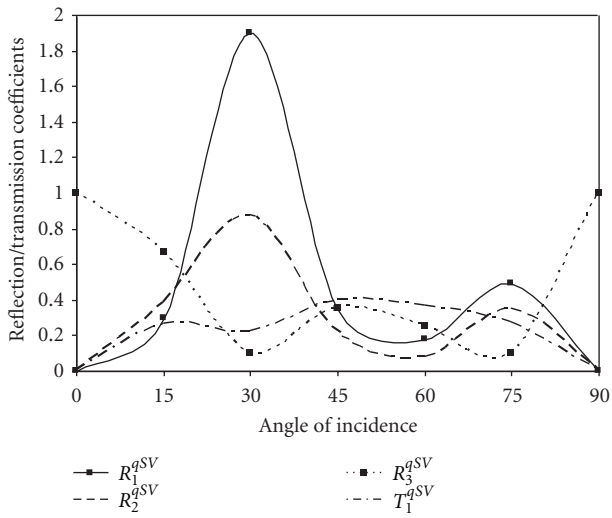

Figure 3: qSV wave incidence at the interface of semiconductor and fluid.

Table 2: Reflection/transmission coefficients in Germanium (Ge) semiconductor.

Angle of incidence (θ)	Reflection/transmission coefficients			
	R_1^{qSV}	R_2^{qSV}	R_3^{qSV}	T_1^{qSV}
0°	0	0	1	0
15°	0.4966	0.0538	0.0281	0.1848
30°	0.2522	0.9208	0.1210	0.4863
45°	0.2023	0.01313	0.8723	0.5759
60°	0.0653	0.0006	0.9326	0.6391
75°	0.2939	0.2980	0.5814	0.7313
90°	0	0.0759	1	0.1094

$30^\circ \leq \theta \leq 60^\circ$; this means that electron wave gets sufficient amount of energy before it dies out at $\theta = 90^\circ$ which is observed to be a new phenomenon here. The reflection coefficient R_3^{qSV} for qSV wave decreases in the range $0^\circ \leq \theta \leq 30^\circ$, increases up to $\theta = 45^\circ$ and remains steady for $45^\circ \leq \theta \leq 60^\circ$ and again decreases to attain its minimum value at $\theta = 72^\circ$, and then sharply increases up to $\theta = 90^\circ$; that is, it recovers from the initial loss of energy. T_1^{qSV} increases in the range $0^\circ \leq \theta \leq 30^\circ$ to attain its maximum value at $\theta = 45^\circ$ and decreases up to $\theta = 90^\circ$. It is also noticed that about 40% of incident energy can be converted to a longitudinal wave in water at incident angles for which the reflected longitudinal wave is cutoff. Thus solid-liquid interface is a perfect reflector.

Figure 4, the variation of reflection coefficients $R_k^{qSV}(k = 1,3)$, and transmission coefficients T_1^{qSV} versus angle of incidence have been plotted. It is noticed that the reflection coefficient R_1^{qSV} increases sharply with increase in the angle of incidence and attains a significantly large value at $\theta = 30^\circ$ and after that it starts decreasing up to a critical angle $\theta = 45^\circ$, which is $\theta = 36^\circ$ in case of stress-free boundary. This is attributed due to high stress generation in the material at this angle of incidence. Beyond this cutoff point whole of

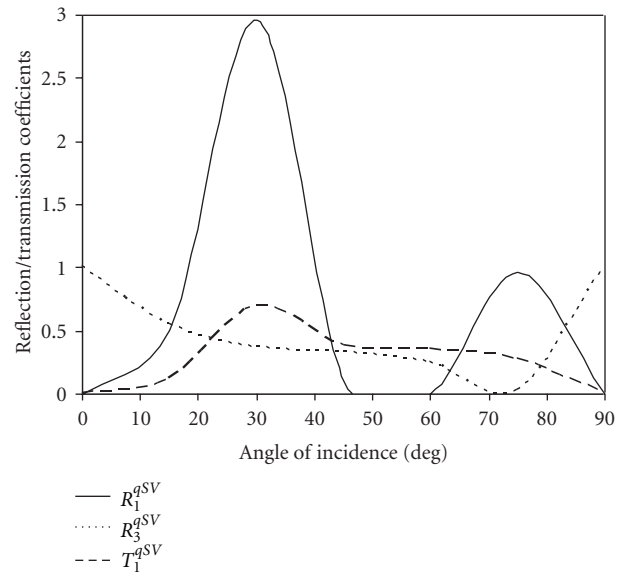

Figure 4: qSV wave incidence at the interface of semiconductor and fluid under electron field equilibrium.

the incident shear wave power is converted into a reflected qSV wave so that $|R_3^{qSV}| = 1$ approximately, although there is a π-phase shift of R_3^{qSV} as θ passes through the critical angle in case of qSV wave incident at the stress-free, isoconcentrated, or impermeable surface of silicon (Si) half-space [20]. Transmission coefficient T_1^{qSV} increases with increase in angle of incidence and attains a maximum value at $\theta = 30^0$; after that it starts decreasing and vanishes at $\theta = 90^0$. This implies that major portion of energy is carried by transmitted wave in comparison to R_3^{qSV} in qSV wave incidence at the interface of semiconductor and fluid under electron field equilibrium.

From Table 2 it is noticed that the behaviors of reflection/transmission coefficients of various waves in germanium (Ge) semiconductor halfspace are almost similar to that in case of silicon (Si) semiconductor except some minor changes in their magnitudes. From Table 3, we concluded that the law of conservation of energy is valid.

9. Conclusions

It is noticed that the magnitude of reflection coefficient (R_1^{qP}) of qP wave decreases with increasing angle of incidence of qP wave in case of silicon (Si) semiconductor material half-space in the range $0^\circ \leq \theta \leq 70^\circ$, and the numerical results show that in case of qP wave incidence maximum energy is carried by transmitted longitudinal wave in the presence of electron wave which takes meager amount of energy. Thus energy transfer is by the phonon of the system, and partition of energy depends upon the angle of incidence. However in case of qSV wave incidence at the surface, transmitted wave becomes more prominent in the presence of electron field and energy is transported in distributed manner among the other waves. The dependence of $R_i^{qP}(i = 1,2,3)$ on $a_i(1,2)$

Table 3: Variation of energy coefficients (Z) in case of (qSV) wave incidence versus angle of incidence (θ) in degree.

Angle of incidence (θ) in degree	0	15	30	45	60	75	90
Energy coefficients (Z)	0.8720	1.3524	2.9889	0.99417	0.0437	1.1923	0.2224

shows that the reflection coefficients do depend upon the frequency of waves and hence are dispersive in character. The study may find application in semiconductor, seismology, and signal processing devices in coated structures.

Appendix

Upon employing the boundary conditions (22) and (25) following system of equations at the surface ($z = 0$) for the n-type semiconductor is obtained

$$\begin{aligned}
&(2\delta^2 k_1^2 \sin^2\theta - \omega^2) A_i e^{\iota k_1 (x\sin\theta)} \\
&\quad + \sum_{j=1}^{2} \left(2\delta^2 k_j^2 \sin^2\theta_j - \omega^2\right) A_j e^{\iota k_j (x\sin\theta_j)} \\
&\quad + \delta^2 k_3^2 \sin 2\theta_3 A_3 e^{\iota k_3 (x\sin\theta_3)} = -\overline{\rho}\omega^2 A_4 e^{\iota k_4 x \sin\theta_4}, \\
&(\delta^2 k_1^2 \sin 2\theta) A_i e^{\iota k (x\sin\theta)} \\
&\quad + \sum_{j=1}^{2} \left(\delta^2 k_j^2 \sin 2\theta_j\right) A_1 e^{\iota k_j (x\sin\theta_j)} \\
&\quad + \left(2\delta^2 k_3^2 \sin^2\theta_3 - \omega^2\right) A_3 e^{\iota k_3 (x\sin\theta_3)} = 0 \\
&\quad - \iota k_1 \cos\theta A_i e^{\iota k_1 (x\sin\theta)} + \sum_{j=1}^{2} \iota k_j \cos\theta_j A_j e^{\iota k_j (x\sin\theta_j)} \\
&\quad - \iota k_3 \sin\theta_3 A_3 e^{\iota k_3 (x\sin\theta_3)} + \iota k_4 \cos\theta_4 A_4 e^{\iota k_4 (x\sin\theta_3)} \\
&\quad - S_1 k_1 \cos\theta_1 A_i e^{\iota k (x\sin\theta)} \\
&\quad + \sum_{j=1}^{2} S_j k_j \cos\theta_j A_j e^{\iota k_j (x\sin\theta_j)} = 0.
\end{aligned} \tag{A.1}$$

The system of (A.1) with the help of (35) becomes

$$AZ_P = C_1, \tag{A.2}$$

where the matrices A and $C_1$are given by

$$A = \begin{bmatrix} \cos 2\theta_3 & \cos 2\theta_3 & -\sin 2\theta_3 & -\overline{\rho} \\ a_1^2\delta^2 \sin 2\theta_1 & a_2^2\delta^2 \sin 2\theta_2 & \cos 2\theta_3 & 0 \\ a_1\delta\cos\theta_1 & a_2\delta\cos\theta_2 & -\sin\theta_3 & a_4\delta\cos\theta_4 \\ a_1 S_1 \cos\theta_1 & a_2 S_2 \cos\theta_2 & 0 & 0 \end{bmatrix}, \tag{A.3}$$

$$\begin{aligned} Z_P &= \left[R_1^{qP}, R_2^{qP}, R_3^{qP}, T_1^{qP}\right]^T, \\ C_1 &= \left[-\cos 2\theta_3, a_1^2\delta^2 \sin 2\theta_1, a\delta\cos\theta_1, a_1 S_1 \cos\theta_1\right]^T. \end{aligned} \tag{A.4}$$

Here $R_k^{qP} = A_k/A_i$, $(k = 1, 2, 3)$ are amplitude ratios of the reflected waves to the incident waves, and $T_1^{qP} = A_4/A_i$ are the amplitude ratios of transmitted wave to the incident wave. Upon applying the appropriate boundary conditions prevailing at the surface of the semiconductor half-space, the amplitude ratios of qSV-wave reflection are given by the matrix equations as

$$AZ_{SV} = C_2, \tag{A.5}$$

where the matrices Z_{SV} and C_2 are given by

$$\begin{aligned} Z_{SV} &= \left[R_1^{qSV}, R_2^{qSV}, R_3^{qSV}, T_1^{qSV}\right]^T, \\ C_2 &= \left[-\sin 2\theta_3, -\cos 2\theta_3, \sin\theta_3, 0\right]^T \end{aligned} \tag{A.6}$$

and the matrices A is defined in (A.3).

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