ACOUSTOELECTRIC EFFECT IN SEMICONDUCTORS

by

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PREFACE

In the last two decades the interaction of acoustic waves with conduction electrons (commonly known as acoustoelectric effect) in semiconductors[1-6] as well as semimetals[7-10] has been studied extensively both experimentally and theoretically. The electron-phonon interaction leads to (i) absorption of the acoustic wave[11], (ii) change in velocity of sound[12] and (iii) acoustoelectric field[13]. The absorption of the wave arises due to the transfer of energy between electrons and phonons, as the electrons cannot completely follow the wave. One of the important aspects of acoustoelectric effect is that amplification rather than absorption occurs under favourable circumstances, e.g., when either an external dc electric field[14] or a temperature gradient[15], applied along the direction of propagation of the acoustic wave, exceeds certain threshold value.The electron-phonon interaction also contributes a real part to the elastic constants, thereby changing the velocity of sound. The acoustoelectric effect arises because the energy transfer between phonons and electrons is accompanied by the momentum transfer. This change of momentum leads to a dc force acting on electrons, which can be looked upon as an acoustoelectric field. The amplification of acoustic waves has been exploited for the fabrication of various devices such as (i) acoustic wave amplifiers[14,16], (ii) acousto-electric oscillators[17] and (iii) delay lines[18]. The study of the acoustoelectric effect may also give valuable information regarding the electron scattering mechanisms, the energy band structure and elastic constants of a semiconductor. In metals, the amplification of the acoustic wave cannot be achieved as the required high electric fields cannot be maintained[19].

Most of the theoretical investigations on absorption/amplification of acoustic waves in semiconductors assume a degenerate velocity distribution of electrons and a constant relaxation time. Jacoboni et al.[20] and Sharma[21], amongst others, pointed out the importance of (i) the nondegenerate (Maxwellian) distribution of electron velocities and (ii) the relevant energy dependence of relaxation times, in the study of acoustoelectric absorption and amplification. Both the investigations employed the Cohen, Harrison and Harrison (CHH) model[22] for the collision term, to account for the scattering of electrons. Recently, Sharma and Kaw[23] have shown that the use of the CHH model[22] for collision term is not valid for energy dependent relaxation times as it fails to conserve the electron density. They have proposed a new collision model which is equally valid for energy dependent relaxation times. Using this, they derived an expression for the absorption coefficient of acoustic wave when acoustic phonon scattering is dominant. They have predicted that the behaviour of the absorption coefficient of the acoustic wave, in the high frequency limit, should be obtained[24] for $q\ell \gg 1$ and not for $\omega\tau_0 \gg \frac{v_o}{v_s}$ as predicted by earlier workers[20]. Using the collision term proposed by Sharma and Kaw[23], Sharma and Singh[25] have developed a theory for the acousto-electric absorption/amplification in nondegenerate semiconductors with parabolic energy bands when acoustic phonon scattering is dominant. Their theory is, however, inapplicable at low temperatures, where the ionized impurity scattering is the dominant scattering mechanism.

In recent past, there has been considerable interest in the effects of the nonparabolicity of energy bands on the propagation of acoustic waves in piezoelectric semiconductors[26,27]. In nondegenerate semiconductors, the nonparabolicity of energy bands, affects the acoustic wave absorption coefficient and the velocity of sound significantly, only when strong magnetic fields are applied[26]. However, in moderately doped semiconductors, the nonparabolicity of energy bands playsa significant role even in the absence of magnetic fields. Recently, Sutherland and Spector[27] reported the effects of nonparabolicity of energy bands on the acoustic wave propagation, however, assuming the relaxation time to be constant.

In a recent paper, Sharma and Singh[15] suggested that an external temperature gradient across piezoelectric semiconductors should lead to the amplification of the acoustic wave. However, they did not calculate the change in the velocity of sound and the absorption/amplification coefficient of the acoustic wave. Also, their theory is not applicable to ferroelectric semiconductors with strain dependent dielectric constants, in which case the effective electron-acoustic wave coupling is much larger than in piezoelectric materials[28].

In the proposed thesis the author has developed theories for the acoustoelectric absorption/amplification in nondegenerate semiconductors with parabolic energy bands. The Boltzmann transport equation approach has been employed. The theories are applicable when (i) both acoustical and optical phonon scattering mechanisms are simultaneously present (applicable at high temperatures) and (ii) ionized impurity scattering is the dominant scattering mechanism (applicable at low temperatures). The effects of the nonparabolicity of energy bands of degenerate semiconductors on the acoustoelectric absorption and the threshold value of the drift velocity, have also been investigated. In addition, theories based on hydrodynamic approach have been developed for acousto-electric absorption/amplification in piezoelectric and ferroelectric semiconductors. It is found that the collision term, proposed by Sharma and Kaw[23], leads to absorption/amplification coefficient significantly different from that predicted by the CHH model. The analyses in chapters I - IV are based on the Boltzmann equation approach and are valid over the entire frequency range of acoustic waves. However, the theories developed in Chapter V, based on hydrodynamic equations, are limited to the case of low frequencies ($q\ell < 1$)

The proposed thesis is divided into five chapters, summaries of which are as follows:-

Chapter-I: Acoustoelectric Absorption in Nondegenerate Semiconductors at High Temperatures

In this chapter we develop a theory for the acoustoelectric absorption of acoustic wave in nondegenerate semiconductors at high temperatures (above 300°K), wherein both acoustical and optical phonon scatterings are simultaneously present. The Boltzmann equation is solved to obtain an expression for the part f_1 of the velocity distribution function of electrons, the space-time variation of which is the same as for the acoustic wave, i.e., as $\exp\{i(\bar{q}\cdot\bar{r}-\omega t)\}$. The interaction between acoustic wave and electrons is taken into account via the deformation potential coupling. The equilibrium distribution function of electron velocities is considered to be Maxwellian. The scattering of electrons in the presence of the acoustic wave has been taken into account by the collision term proposed by Sharma and Kaw[23]. The energy bands of the semiconductor are considered to be parabolic. The expression for f_1 is used to obtain an expression for the current density (due to acoustic wave) which, in turn, leads to the conductivity tensor. Using the expression for the conductivity, and following Harrison[29] and Spector[16], we obtain an expression for the absorption coefficient of the acoustic wave. The theory is valid for the entire frequency range of the acoustic wave. The variation of the absorption coefficient with acoustic wave frequency in a nondegenerate semiconductor at various temperatures has been numerically investigated for relevant parameters. The results have been compared with the case when only acoustical phonon scattering is considered to be dominant. It is seen that the results obtained in the two cases differ significantly in the low frequency region.

Chapter-II: Absorption/Amplification of Acoustic Waves in Nondegenerate Semiconductors at Low Temperatures

In this chapter we develop a theory for the absorption/amplification of acoustic waves in semiconductors with parabolic energy bands. The theory is applicable at low temperatures (4-100°K) because the ionized impurity scattering is the dominant scattering mechanism. The Boltzmann equation is solved for the distribution function of electron velocities. The ionized impurity scattering is incorporated in the theory by the use of the collision model suggested by Sharma and Kaw[23]. The external dc electric field is along the direction of propagation of the acoustic wave. The interaction between the acoustic wave and electrons is again via the deformation potential coupling. Using the expression for f_1^1, the part of the distribution function, the space-time variation of which is the same as for the acoustic wave, the conductivity and hence the absorption/amplification coefficient is calculated. Comparison of the results with those obtained using the CHH model[22] for collision term shows that the absorption/amplification of the acoustic wave differs significantly at low frequencies. However, the results obtained at high frequencies are more or less the same.

Chapter-III: Absorption of Acoustic Waves in Nonparabolic Semiconductors

This chapter considers the acoustoelectric absorption in nonparabolic degenerate semiconductors. In contrast to the analyses of chapters I and II, we write down the Boltzmann equation in k-space and obtain a solution for the distribution function of the electron velocities. Since the nonparabolic semiconductors (III-V group compound semiconductors) exhibit piezoelectric properties also, the interaction of acoustic wave with electrons is taken into account via both the deformation potential coupling and the piezoelectric coupling. The modified expression for the ionized impurity scattering of electrons for the case of nonparabolic degenerate semiconductors is obtained and is incorporated in the theory through the modified collision model[23]. The nonparabolicity of energy bands is accounted for using the Kane model[30]. Finally, an expression for the absorption coefficient is obtained as a function of the energy gap and degeneracy parameter. The theory is applicable to n-InSb at low temperatures (4-100°K). Numerical results indicate that the absorption coefficient initially increases with degeneracy parameter, attains a maximum and then decreases for sufficiently high values of degeneracy parameter. It is also seen that an increase in the nonparabolicity of energy bands leads to decreased absorption of the acoustic wave.

Chapter-IV: Acoustic Wave Absorption/Amplification in Nonparabolic Semiconductors

In this chapter we extend the theory of chapter III for acoustoelectric absorption in nonparabolic degenerate semiconductors to the case when an external dc electric field is applied along the direction of propagation of the acoustic wave. Assuming the ionized impurity scattering as the main scattering mechanism of electrons, and following the method of chapter II, we derive an expression for the absorption/amplification coefficient of the acoustic wave, valid in the entire frequency range of the acoustic wave. The consideration of the ionized impurity scattering as the dominant scattering mechanism, however, limits the applicability of the theory to low temperature range (4-100°K). It is seen from the results that an increase either in the nonparabolicity factor or in the degeneracy parameter leads to decreased threshold drift velocity. The amplification coefficient exhibits peak behaviour with degeneracy parameter.

Chapter-V : Absorption/Amplification of Acoustic Wave due to Temperature Gradient

Part-A: Piezoelectric Semiconductors

Recently, Sharma and Singh[15] suggested that amplification could be obtained by maintaining a temperature gradient in the direction of propagation of acoustic wave. In this part, we derive expressions for the absorption/amplification coefficient and the change in the velocity of sound in the presence of an external temperature gradient. The interaction between the acoustic wave and electrons is considered to be purely piezoelectric. For a typical n-InSb sample, the amplification coefficient as well as the change in the velocity of sound is found to increase with temperature gradient. The theory is based on hydrodynamic equations and is, therefore, limited to the case of low frequencies of the acoustic wave, i.e., $ql < 1$.

Part-B: Ferroelectric Semiconductors

A hydrodynamic theory is developed for acoustic wave absorption/amplification in ferroelectric semiconductors in the presence of an external temperature gradient. The main result of this part is that the acoustic wave can be amplified even when the drift velocity of electrons is less than the velocity of sound. Calculations for $SrTiO_3$ indicate that, under favourable circumstances, decrease in the threshold value of the drift velocity as large as 90% can be obtained.

The above work has resulted in the following publications/communications:-

1. Acoustoelectric Absorption in Nondegenerate Semiconductors, Sol.Stat.Elect. 19, 403 (1976).
2. Amplification of Acoustic Waves in Semiconductors with Dominant Ionized Impurity Scattering, Sol. Stat. Elect. 19, 1029 (1976).
3. Acoustoelectric Absorption in Degenerate Nonparabolic Semiconductors, J.Appl.Phys. (In Press).
4. Acoustic Wave Absorption/Amplification in Nonparabolic Degenerate Semiconductors (Communicated, 1977).
5. Absorption/Amplification of Acoustic Waves in Piezoelectric Semiconductors in the presence of External Temperature Gradients (Communicated, 1977)

6. Absorption/Amplification of Acoustic Waves in Materials with Strain Dependent Dielectric Constants in the Presence of External Temperature Gradients (Communicated, 1977).

In addition to above publications/communications, the author has also been associated with the following publication which is not included in the present thesis:

1. Lowering of plasma frequency in semiconductors due to quantum magnetic fields, Phys. Stat. Sol. (a) 31, K103 (1975).

CONTENTS

III ABSORPTION OF ACOUSTIC WAVES IN NONPARABOLIC SEMICONDUCTORS

IV ACOUSTIC WAVE ABSORPTION/AMPLIFICATION IN NONPARABOLIC SEMICONDUCTORS

V ABSORPTION/AMPLIFICATION OF ACOUSTIC WAVE DUE TO TEMPERATURE GRADIENT