INTERACTION OF BULK AND SURFACE ACOUSTIC WAVES WITH CONDUCTION ELECTRONS IN PIEZOELECTRIC SEMICONDUCTORS

by

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PREFACE

The interaction between electrons and lattice vibrations is one of the fundamental interaction processes in solids. Parmenter [1] was the first to describe the interaction between electrons and acoustic waves in solids. The interaction between acoustic waves and electrons commonly known as 'Acoustoelectric Effect' has been the object of numerous theoretical and experimental studies in the past as well as in the present[1-14].

The fact that the electron-acoustic phonon interaction (EAWI) can lead to the amplification of acoustic waves by the application of dc electric field has been commercially exploited for the fabrication of delay lines, acoustoelectric amplifiers, acoustoelectric oscillators etc. Since the acoustic wave is 10^5 times slower than the electromagnetic waves, it enables one to design and fabricate very sophisticated signal processing devices which are orders of magnitude smaller in size than its electromagnetic counterpart and perform the same functions. In addition to this EAWI also gives useful information about the band structure of the material and scattering mechanisms. During the last decade the acoustoelectric activity has been shifted from bulk waves to surface acoustic waves. This is because of the ease with which the propagation of the surface waves can be controlled and guided.

EAWI in general leads to three different effects in solids viz. (i) it results in the absorption of the wave, (ii) contributes to the value of elastic constants and hence changes the acoustic wave velocity, and (iii) leads to the appearance of an electric field called Acoustoelectric Field. Hutson[2] first pointed that large parametric interaction between electrons and acoustic phonons in piezoelectric semiconductors. Later, Hutson et.al [3] demonstrated for the first time that it was possible to amplify acoustic waves in CdS by the application of dc electric field. In a subsequent paper White[4] gave a detailed theory for the amplification of acoustic waves in piezoelectric semiconductors . Since then piezoelectric semiconductors have been extensively used to study the EAWI and in the fabrication of acoustoelectric and signal processing devices.

The present thesis is mainly concerned with the theoretical study of the amplification of acoustic waves in piezoelectric semiconductors. In addition, second harmonic generation and nonlinearity arising in electron mass and collision frequency due to EAWI have also been considered.

There are three different theoretical approaches extensively employed to study the EAWI in piezoelectric semiconductors.

(i) Phenomenological approach,

(ii) Boltzmann transport equation approach, and (iii) Quantum mechanical approach.

In the phenomenological approach it is assumed that the average velocity of the electron is equal to the drift velocity. This requires that during the time acoustic wave travels a distance of one wave length, the electron undergoes many collisions. This approach is therefore limited to the low frequency region i.e. for $ql \ll 1$ (q is the wave number of the acoustic wave and l is the mean free path of the electron). Nevertheless the condition $ql \ll 1$ can be met over a wide range of frequencies of interest in piezoelectric semiconductors such as CdS[15] . The Boltzmann equation approach is valid for the entire frequency range of acoustic wave and has been widely used especially for high mobility semiconductors such as InSb. The quantum mechanical approach is valid for very high frequencies and strong electric and magnetic fields.

In the present thesis we have used both phenomenological and Boltzmann equation approaches.

In this thesis we have first developed a theory for the amplification of acoustic waves by the application of an electron density gradient. The importance of this method of amplification lies in the fact that extrinsic semiconductors doped by the different processes have a built-in space-dependent impurity concentration and have a carrier concentration gradient. In such semiconductors, therefore, when the acoustic wave propagates along the density gradient (decreasing density gradient), the wave gets amplified even when there is no dc field present in the semiconductor.

Most of the theoretical works based on Boltzmann approach for the calculation of absorption/amplification coefficient have used Cohen, Harrison and Harrison (CHH) model [16] of the collision term. Sharma and Kaw[17], however pointed out that CHH model of collision term is not valid for energy dependent relaxation time since it does not conserve the particles. They gave an alternate model which was valid even for energy dependent relaxation time. More recently, Sharma and Kaw[18] have shown that one can also use CHH model of collision term provided that it is used to calculate the current density on account of the electrons saving velocity between v and v + dv . The total current density then is obtained by performing the summation over the entire range of velocity (v = 0 to v =∞). In recent years Sharma and Singh[19] and Sharma and Sharma[20] have calculated the amplification coefficient in non-piezoelectric semiconductors for various scattering mechanisms viz. (i) optical phonon scattering (ii) acoustic phonon scattering. There is no theory which is applicable to piezoelectric semiconductors (e.g. CdS) where the piezoelectric scattering is one of the important scattering mechanisms. In this thesis we have developed a theory for the absorption/amplification of acoustic wave in piezoelectric semiconductors by considering the combination of piezoelectric and ionized impurity scatterings at low temperatures (20 to 100 K) and piezoelectric and acoustic phonon scatterings from 100 to 300 K.

Another problem we have investigated is the amplification of Bleustein-Gulyaev waves (BG waves). BG waves have several advantages over the other types of surface waves for a number of reasons viz. (i) their particle displacement is simpler, (ii) their propagation path is less affected by surface defects, (iii) they have got deeper penetration depth, and (iv) they can transport much more power. Soluch[21] has studied the amplification of BG waves in layered structure. Kuzmany et. al[22] have studied the amplification of BG waves in strain dependent materials. Roy and Cambon[23] extended the work of Rouzeyre and Cambon[23] on the depth of penetration of BG waves in CdS. They have however treated piezoelectric property as a small perturbation and have considered only semiconducting property of CdS for a small part of its thickness. In contrast to their work, we have studied the amplification of BG waves in CdS by taking into account its piezoelectric as well as semiconducting properties. Following the work of Viktorov[25] on Rayleigh waves absorption in CdS, we have solved the necessary differential equations and obtained a simple expression for amplification coefficient.

EAWI in piezoelectric semiconductors also leads to a number of interesting nonlinear phenomena.One of such is the change in electron mass and collision frequency due to the propagation of acoustic waves. This change arises due to the electrons whose temperature is modified appreciably because of the presence of the field associated with the wave. We have developed a phenomenological theory to investigate the effect of EAWI on electron effective mass and collision frequency. This study also leads to an interesting result that the threshold amplification should occur at the drift velocities greater than the acoustic wave velocity.

The other nonlinear problem we have studied is the generation of acoustic second harmonic. Most of the theories on acoustic second harmonic generation assume a uniform static electric-field intensity. In reality this is not true even in trap free samples and one can show that the electric field intensity varies as the square root of the sample length. By considering this fact, we have developed a phenomenological theory to study the second harmonic generation of acoustic waves in piezoelectric semiconductors. We have derived an expression for the power associated with the second harmonic in terms of power associated with the fundamental. We have also discussed our results based on numerical calculation for CdS sample.

The entire work of this thesis may be devided into five chapters, whose brief summaries are given below:

Chapter I :

Amplification of Acoustic Waves in Piezoelectric Semiconductors by Applications of an Electron Density Gradient

It is proposed that it should be possible to amplify acoustic waves in a piezoelectric semiconductor having an electron density gradient along the direction of propagation of the acoustic wave. An expression for the threshold amplification condition in terms of thickness and electron concentrations at the two faces of the semiconducting slab has been obtained using hydrodynamic equations. For a typical case of InSb it has been shown that the threshold amplification should occur if the two faces of the semiconducting slab have densities 1.0 x $10^{14}/\text{cm}^3$ and 5.3 x $10^{13}/\text{cm}^3$, respectively.

Chapt r II :

Dependence of Acoustoelectric Amplification on Scattering Parameter in Doped Piezoelectric Semiconductors

Part A: Piezoelectric and Ionized Impurity Scatterings

Following the new formalism of Sharma and Kaw[18] for energy dependent relaxation times, the Boltzmann equation has been used to calculate the conductivity tensor and absorption coefficient when an acoustic wave propagates through a nondegenerate piezoelectric semiconductor in the presence of an external dc electric field. The mixed scattering of electrons by ionized impurity as well as by piezoelectric potential have been taken into account. The dependence of threshold drift velocity, required for amplification, on the scattering parameter ν_{op}/ν_{oi} (ν_{op} and ν_{oi} are the equilibrium collision frequencies correspond to piezoelectric potential and ionized impurity scattering respectively) has been investigated.

Part B: Piezoelectric and Acoustic Phonon Scatterings.

The Boltzmann transport equation has been solved in a similar way to obtain the conductivity tensor and absorption coefficient when an acoustic wave propagates through a piezoelectric semiconductor in the presence of dc electric field. The energy dependent relaxation time and the scatterings due to piezoelectric potential and deformation potential have been considered. In addition, the isotropic part of the distribution function is assumed to be dc field dependent. The effect of frequency of the wave and scattering parameter ν_{op}/ν_{oa} (ν_{oa} is the equilibrium collision frequency corresponds to acoustic phonon scattering) on amplification coefficient has been studied. We have also presented some results based on numerical calculation for n-CdS in the form of graphs and discussed them in the last section.

Chapter III :

Amplification of Bleustein-Gulyaev Waves in Cadmium Sulphide

A kind of surface acoustic wave having a pure transverse particle displacement in piezoelectric crystal is called Bleustein-Gulyaev Waves [26,27]. The propagation of such waves in semiconducting piezoelectric crystals of class 6 has been studied theoretically. By solving the partial differential equations representing the EAWI in the presence of a dc electric field separately for semiconducting and vacuum regions and using the boundary conditions, an expression for amplification coefficient is obtained. The effect of diffusion is also taken into account. Numerical results are presented for the semiconducting CdS.

Chapter IV :

Propagation of Acoustic Waves in Semiconductors

Part A : Change in Electron Mass and Collision Frequency

A phenomenological theory is developed to study the relative change in electron mass and collision frequency when an acoustic wave propagates through piezoelectric semiconductors. The results based on numerical calculations show that this change is appreciable at lower temperatures for n-CdS . It has been calculated that the change in collision frequency is as much as 7% for 0.5 watt acoustic power.

Part B : Threshold Acoustic Wave Amplification Condition

Experimental studies on the acoustoelectric amplification in piezoelectric semiconductors show that the attenuation of an acoustic wave crosses over to its amplification when electron drift velocity exceeds the acoustic wave velocity. We propose that the nonlinearity in electron mass and collision frequency arising due to the electric vector of the field associated with the wave can also explain this behaviour.

Chapter V :

Acoustic Second Harmonic Generation in Piezoelectric Semiconductors: Effect of Nonuniform Electric Field Intensity

Acoustic second harmonic generation is studied in nondegenerate piezoelectric semiconductors in the presence of dc electric field longitudinal to the direction of propagation of the acoustic wave. The static electric-field intensity as well as the carrier concentration are taken as nonuniform along the propagation direction even in trap free samples. These assumptions modify the final results of our theory from the results obtained by earlier theories considerably. It is also found that the power thus calculated for the second harmonic is enhanced . Comparison with the available experimental results show a qualitative agreement. We have used phenomenological theory and that restricts our analysis to the low frequency region only.

The forementioned work has resulted in the following publications/communications:

1. Amplification of acoustic waves in piezoelectric semiconductors by applications of an electron density gradient- Physica Status Solidi (a) 62, K 153 (1980).
2. Change in electron mass and collision frequency due to acoustic wave propagation in piezoelectric semiconductors- Physica Status Solidi (b) 109, 119 (1982).
3. Dependence of threshold acoustoelectric amplification on scattering parameter in doped piezoelectric semiconductors- J. Phys. Soc. Japan 51, 2181 (1982).
4. Effect of nonlinearity in electron mass and collision frequency on acoustoelectric amplification in semiconductors- Communicated (1982).
5. Amplification of Bleustein-Gulyaev waves in cadmium sulphide- Communicated (1982).
6. Acoustic second harmonic generation in piezoelectric semiconductors : Effect of nonuniform electric field intensity- accepted for publication in J.Appl.Physics.

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