INTERACTION OF ACOUSTICAL AND ELECTRICAL FIELDS IN SEMICONDUCTORS

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PREFACE

The interaction between acoustic waves and electrons in solids commonly known as 'Acoustoelectric Effect', has been the object of numerous theoretical and experimental studies, as it shows great promise in physical as well as engineering problems. Some of the important applications which embrace acoustoelectric effect are: acoustic-wave amplifiers, long signal delay lines, determination of electronic band structure, determination of elastic constants, etc.

The revival of scientific interest in acoustoelectric effect in semiconductors was earmarked by the observation that in an applied electric field the drifting electrons can amplify a propagating acoustic wave. This was shown experimentally[1], and explained by a phenomenological analysis[2], for the interaction between electrons and acoustic waves in piezoelectric semiconductors (e.g. CdS). The particular model used by White[2] for describing the electron dynamics is appropriate when (i) drift velocities are small as compared to the thermal velocity (ii) collision frequencies are large compared to the acoustic wave frequency, and (iii) electron mean free path ℓ is small compared to the wavelength ($\lambda = 2\pi/q$) of the acoustic wave (i.e. $q\ell \ll 1$).

Subsequent studies[3] were made to extend the theory for high frequencies $q\ell \gg 1$ and inclusion of the effects of an externally applied magnetic field[3]. Following the discovery of acoustic wave amplification in piezoelectric semiconductors, it was proposed that acoustic waves can also be amplified in semiconductors where the electron-phonon interaction arises from sources other than piezoelectric potential[3,4]. The main types of coupling mechanisms in addition to piezoelectricity are electromagnetic, deformation potential, magnetoelastic, and the dependence of the dielectric constant on the deformation of the solid; the relative importance of these mechanisms is determined by the type of material under consideration.

The acoustoelectric effect besides producing linear gain or loss of a single acoustic wave also couples together different acoustic waves as a result of nonlinearities in the electron-phonon interaction. Interest in this frequency mixing of acoustic waves was stimulated by the observation of ultrasonic harmonic generation in CdS[5,6]. A few years following this observation many phenomenological theories were developed to study the various aspect of frequency mixing and up and down conversion[7-10]. More recently, it was pointed out that by applying static electric and magnetic fields, the harmonic yield in piezoelectric semiconductors can be enhanced considerably[11,12]. However no attempt appears to have been made to explore the possibility of achieving higher harmonic yields by using solids other than those showing strong piezoelectric behaviour. In Part I of this thesis we consider frequency mixing, and up and down conversion in non-piezoelectric semiconductors and derive optimum conditions for maximum harmonic yield. Moreover a comparative study of the role of different coupling mechanisms has also been carried out in Part I of this thesis.

Another fascinating allied field is the study of electron-phonon-photon interaction in semiconductors[13-15]. The earlier theories for describing the interaction of acoustic wave with electrons are based on energy independent carrier relaxation time. This restriction makes these theories inapplicable for semiconductors in the microwave region ($q\ell \geqslant 1$). In Part II of this thesis we have developed an elaborate theory based on Boltzmann's Transfer Equation for the linear electron-phonon-photon interaction, incorporating the proper scattering mechanism and consequent energy dependence of carrier relaxation time (in nondegenerate semiconductors).

The growing interest in nonlinear interactions motivated us to investigate nonlinear electron phonon-photon interaction in piezoelectric semiconductors. This investigation led us to some very interesting results regarding the acoustic harmonic yield, to which ample sapce has been devoted in Part II of this thesis.

The important features of the investigations reported in Part I and II are presented as follows:-

PART - I

The possibility of achieving large harmonic generation and parametric interaction of acoustic waves in piezoelectric semiconductors was first realized by Hutson[16]. Harmonic generation in CdS has recently been reported by Tell[5] and Kroger[17]. When an acoustic wave propagates in a semiconductor, the self consistent field produced as a result of various coupling mechanisms in semiconductors gives rise to bunching of the carriers. This bunching of the carriers results in the familiar attenuation and amplification of the wave depending upon whether the drift velocity of the carriers, in an applied electric field is smaller or greater than the acoustic wave velocity. When more than one wave is present, interactions occur between the different waves because the bunches produced by one wave interact with the electric field due to other waves; more precisely, the electrons are simultaneously bunched by the fields of all the waves. This interaction of self consistent fields associated with different waves takes place by virtue of the nonlinearities in the electron-lattice interaction. The self-consistent field is determined by the appropriate coupling mechanism. Recently a number of analyses of nonlinear acousto-electric interaction in the low[5,7-9,11,12] and high frequency regimes[10] using the piezoelectric coupling mechanism have been formulated. Since all solids exhibit deformation while only few crystals show piezoelectricity[3] we have investigated in Chapter I, the behaviour of nonlinear acoustoelectric interaction in semiconductors in which deformation potential is the dominant carrier scattering mechanism. Moreover the relative importance of the scattering mechanisms have been dealt in depth in Chapter I.

Another interesting feature which is characteristic of both piezoelectric and nonpiezoelectric semiconductors is the dependence of the dielectric constant on the deformation of the semiconductors[4], thereby giving rise to nonlinearities in the electron-phonon interaction. A phenomenological treatment of nonlinear acousto-electric interaction in solids on account of this nonlinearity has been considered in Chapter II.

In the high frequency range ($ql \gg 1$) the macroscopic theory fails, and is replaced by a more rigorous theory based on Boltzmann's Transfer Equation[3,10]. So far the theories for the behaviour of nonlinear acoustoelectric interaction[10] in this frequency range were valid only when the carrier relaxation time is assumed to be independent of energy, which is at best a crude assumption[18-20]. In Chapter III we have investigated the behaviour of nonlinear acoustoelectric interaction in semiconductors taking the proper scattering mechanism and consequent energy dependence of carrier relaxation time into account. The result of this investigation led us to some very interesting features of the dependence of the acoustic harmonic yield on the nature of energy dependence of the carrier relaxation time. The following is the chapterwise summary of Part I.

Chapter I

This chapter reports an investigation of acoustic wave second harmonic generation as a result of nonlinear electron-phonon interaction in semiconductors due to deformation potential coupling. Moreover in semiconductors where both piezoelectric and deformation potential effects are present, the theory has been used to study the relative dominance of the coupling mechanisms and to derive optimum conditions for maximum harmonic generation. The chapter has been divided into two sections. Sec.A is devoted to the study of the second harmonic generation arising solely because of the interaction of the self consistent fields associated with acoustic waves of different frequency. A comparative study of the role of deformation and piezoelectric scattering mechanism has revealed some interesting points of difference. The effect of static electric and magnetic fields on the behaviour of harmonic generation has been investigated in Sec.B of this chapter.

Chapter II

This chapter presents a study of frequency mixing up and down conversion of acoustic waves resulting on account of nonlinearities in electron-phonon interaction due to the strain dependence of the dielectric constant (SDDC). It is found that this electron-phonon coupling mechanism through SDDC is the dominant coupling in crystals with large dielectric constant. Moreover the presence of static electric and magnetic fields alters the behaviour of nonlinear acoustoelectric interaction (due to SDDC). This chapter has been divided in the following two sections.

Section 'A'

Acoustic wave second harmonic generation in materials with strain dependent dielectric constants is investigated in presence of static electric and magnetic fields. It is shown that for materials with large dielectric constants, the second harmonic yield is much larger in magnitude than in materials exhibiting piezoelectricity.

Section 'B'

In this section the phenomenon of frequency mixing of acoustic waves in semiconductors as a result of electron-phonon interaction through a strain dependent dielectric constant (SDDC) has been analytically investigated. The dependence of subharmonic generation on account of electron-phonon interaction due to SDDC on the various parameters i.e. $\omega, B, \gamma,$ etc., displays marked differences with that in case of piezoelectric interaction, studied earlier by Conwell and Ganguly[7] and Spector[12]. Numerical results have been presented for a typical case of a $BaTiO_3$ sample. It is found that for such materials (with large dielectric constants) the electron-phonon interaction effects due to SDDC are more important than piezoelectric interaction determining the subharmonic generation.

Chapter III

In contrast to the earlier work on nonlinear acoustoelectric interaction, the energy dependence of carrier relaxation time for acoustic phonon scattering has been taken into account in solving the Boltzmann's transfer equation to investigate the generation of second harmonic acoustic wave in non-degenerate semiconductors in the presence of an external dc electric field. The results show that the fundamental and the second harmonic acoustic waves can be amplified under appropriate conditions, in both the low frequency ($q\ell \ll 1$) and high frequency regions ($q\ell \gg 1$). The conditions for amplification in the $q\ell < 1$ case is $\langle v_d \rangle / v_s \geqslant 1$, while in the high frequency region the condition for amplification is $\frac{\langle v_d \rangle}{v_s} \geqslant \frac{4[n^2\omega^2/\nu_0^2+1]}{3[(n^2\omega^2/\nu_0^2)\pi+2]}$; $n = 1, 2$ for the fundamental and second harmonic respectively. If we take into account the energy dependence of the relaxation time the threshold drift velocity required for amplification is less than that predicted in earlier theories[10] based on constant relaxation time approximation.

PART - II

The growing interest in the interaction of the electromagnetic field with the acoustic waves is associated with the importance of achieving an efficient transfer of modulation from the electromagnetic field to an acoustic wave of different frequency. Ephstein[13] proposed a phenomenological (low frequency) theory of acoustic wave propagation in semiconductors in the presence of an electromagnetic field. Later this was generalized to higher frequencies by Pantell and Soohoo[14] who adopted a quantum mechanical approach. Although these theories[13,14] provide some physical insight into the problem of the interaction of acoustic wave with electromagnetic field in semiconductors, they are inappropriate for cases of practical interest because of the inherent assumptions. One such assumption is the energy independence of the carrier relaxation time, which is not justified in semiconductors[18-20]. The second assumption of weak oscillating signal limits the utility of the theory for a practical acoustic wave amplifier. In chapter IV of this thesis we develop a realistic theory based on Boltzmann's transfer equation, incorporating the energy dependence of the carrier relaxation time and also making allowance for large magnitudes of the electromagnetic field.

The earlier investigations[13-15] which have been carried out so far on the interaction of acoustic waves with electrons in the presence of an electromagnetic field, were limited to the study of linear acoustoelectric interaction only, viz. estimating the change in the linear attenuation or amplification coefficient, produced as a result of the application of an electromagnetic field. The interesting problem of nonlinear electron phonon-interaction in the presence of an electromagnetic field has been investigated in Chapter V from a phenomenological point of view and the optimum conditions for maximum acoustic harmonic flux have been obtained. This mechanism should find practical applications in obtaining higher intensity acoustic harmonics, thereby facilitating the detection and generation of harmonics.

The following is the chapterwise summary of Part II.

<u>Chapter IV</u>

The energy dependent carrier relaxation time has been incorporated in the study of electron-phonon-photon interactions in nondegenerate semiconductors in the presence of an external dc electric field. The Boltzmann's transfer equation has been used to obtain electronic absorption and gain coefficients. The scattering of charge carriers with acoustic phonons has been assumed to be the dominant scattering mechanism. The results show that the percentage change in the gain constant is $\sim 15\%$ for $q_v \ell < 1$ and $\sim 30\%$ for $q_v \ell > 1$ (for intense electromagnetic fields). For weak oscillating electric field ($E_{a.c} < \frac{\omega v_s}{\mu \Omega}$ for $q_v \ell > 1$ and $E_{a.c} < \frac{m \Omega^2}{q_v \ell}$ for $q_v \ell > 1$ where ω, Ω are the frequencies of acoustic wave and the oscillating electric field, v_d is the average drift velocity of the carriers, v_s the sound velocity, m is the mass and μ is the mobility of the carriers) no significant percentage change is observed in the gain constants for both the frequency domains.

Chapter V

The nonlinear electron-phonon interaction in presence of an electromagnetic field is the subject of this chapter. In Sec.A of this chapter we discuss the various methods of optimizing ultrasonic second harmonic generation in presence of an external static electric field. The affect of an externally applied static magnetic field at different angles to the direction of wave propagation has been studied in Sec.B.

Section A

The phenomenological approach has been used to study analytically the accoustic wave second harmonic generation in piezoelectric semiconductors in the presence of the dc electric and an oscillating electromagnetic field (OEF). It has been suggested that the second harmonic acoustic flux (SHAF) can be enhanced considerably by the application of an OEF polarized in the direction of the propagating acoustic wave. The SHAF exhibits a maximum at $\Omega = \omega$, where Ω is the frequency of the OEF and ω is the frequency of the acoustic wave. The SHAF also shows a maximum at dc electric fields for which the average drift velocity of the carriers is equal to the velocity of sound. It is found for a typical case of n-type nondegenerate InSb that the SHAF is enhanced by a factor of 10^3 over its value in the absence of OEF. The analysis is valid in the low frequency region only ($q\ell \ll 1$).

Section B

A phenomenological theory of ultrasonic second harmonic generation in piezoelectric semiconductors, in the presence of dc electric field, dc magnetic field, and an oscillating electric vector of an em field is developed. The theory predicts a transfer of electromagnetic energy to acoustic energy at different frequency. The conversion efficiency is maximum at $\Omega = \omega$. It is seen from the results that the second harmonic yield is maximum for certain optimum values of dc electric and magnetic fields. As expected, in the absence of electromagnetic field, our expression for the acoustic flux in the second harmonic reduces to that obtained earlier by Spector[11].

The thesis is partly based on the following publications:

1. Nonlinear excitation of acoustic waves in nondegenerate semiconductors (communicated 1973).

2. Acoustic wave second harmonic generation in nondegenerate semiconductors in presence of magnetic field (communicated 1973).
3. Acoustic wave second harmonic generation in materials with strain dependent dielectric constants (accepted J.Appl.Phys. 1973).
4. Frequency mixing of acoustic waves in semiconductors (communicated 1973).
5. Acoustic harmonic generation in nondegenerate semiconductors in presence of dc electric field (accepted Phys.Stat.Solidi (a) 1973).
6. Optimum acoustic wave second harmonic generation in piezoelectric semiconductors (accepted Int.J. of Phys. and Chem. of Solids 1973).
7. Ultrasonic harmonic generation in piezoelectric semiconductors in presence of electromagnetic field and a magnetic field,'Phys.Stat.Solidi (a), <u>20</u>, 237-247 (1973).
8. Stimulated Electronphonon-photon interaction in nondegenerate semiconductors considering energy dependent carrier relaxation time (communicated 1973).

In addition to the above publications the author has also been associated with the following publications which have not been included in the present thesis.-

1. Propagation of a gaussian beam in planar and cylindrically inhomogeneous media: comparison of model analysis and approximate approaches, Optica Acta, <u>19</u>, 941-950 (1971).
2. Nonlinear mechanisms for self focusing and propagation of microwave pulses in semiconductors, J.Appl.Phys., <u>44</u>, 1699-1705(1973).
3. Damping criterion for the focusing of laser beams in semiconductors, J.Phys.D., <u>6</u>, 363 (1973).

4. Effect of self-focusing on the self distortion of amplitude modulated microwaves in non-parabolic semiconductors, Opto-Electronics (UK), 5, 131 (1972).

5. Microwave faraday rotation and self focusing of helicon waves in n-InSb, J.Appl.Phys. 44, 3153 (1973).

6. **Analysis** of propagation in a Selfoc fibre: the axial field component and the effect of multiple reflections, Opto-Electronics(UK), 4, 51 (1972).

CONTENTS

Part-II

Section A: Optimum Acoustic-Wave Second Harmonic Generation in Piezoelectric Semiconductors

Section B: Ultrasonic Harmonic Generation in Piezoelectric Semiconductors in Presence of Magnetic Field.