INTERACTION OF ACOUSTIC WAVES WITH CONDUCTION ELECTRONS IN SEMICONDUCTORS

by

Shri Pal Singh

Thesis submitted to the Indian Institute of Technology, Delhi
for the award of the Degree of
DOCTOR OF PHILOSOPHY

Department of Physics
Indian Institute of Technology, Delhi

October, 1975

ACKNOWLEDGEMENTS

I am deeply indebted to Professor M.S.Sodha and Dr. S.K.Sharma for their valuable guidance, kind encouragement and inspiration throughout the work.

I am also grateful to Professor A.K. Ghatak, Head of the Physics Department for his advice, encouragement and keen interest in the work. Special thanks are due to Dr. D.P. Tewari and Dr. A.K.Agarwal for many stimulating discussions and important suggestions. My sincere thanks are due to Dr.V.K.Tripathi, Shri S.S.Sharma, Shri N.C.Srivastava and also to Sarva-Shri R.P.Sharma, S.C. Kaushik, Arun Kumar and other colleagues of Electro-Physics Group for their help and cooperation.

Thanks are also due to Shri T.N.Gupta for typing the thesis and related manuscripts very efficiently.

The financial support of Council of Scientific and Industrial Research is gratefully acknowledged.

Shri Pal Singh
(Shri Pal Singh)

PREFACE

During the last 15 years a sizable number of papers[1,2], both theoretical as well as experimental, have been published on the electron-phonon interaction in semiconductors because it gives the useful information regarding the band structure of the semiconductor. The fact that the electron-phonon interaction can lead to amplification of acoustic wave by the application of a suitable dc field, has been commercially exploited for the fabrication of delay lines, acousto-electric amplifiers, acoustoelectric oscillators etc. The other interesting phenomena which arise as a consequence of the electron-phonon interaction are the generation of second harmonic of acoustic waves and the convolution of surface acoustic waves.

In the present work, the author has derived an expression for the absorption coefficient of an acoustic wave in the presence of a temperature gradient. It is proposed that it should be possible to amplify the acoustic wave by applying a strong temperature gradient. The author has also studied the phenomena of second harmonic generation of acoustic waves and convolution of surface acoustic waves in semiconductors. The work of the proposed thesis may be divided into two parts.

Part I deals with the attenuation and amplification of acoustic waves and has been further divided into two chapters.

In chapter I, an elementary theory for the amplification of an acoustic waves due to the application of external temperature gradients has been developed. The theory is valid in the limiting case of low frequencies i.e. $q\ell \ll 1$ (q is the wave vector of the sound wave and ℓ is the mean free path of the electron) as it is based on the use of hydrodynamic equations. The theory predicts that the acoustic wave can be amplified by just maintaining the two faces of a semiconducting slab of 0.8 mm thickness at 77°K and 195°K respectively.

Most of the theoretical papers[3] on the calculation of absorption coefficient, use a highly degenerate distribution function and a relaxation time which is independent of the electron energy. Recently, however, Jacoboni and Prohofsky[4] and Sharma[5] have realized the importance of using the appropriate distribution function and the relevant energy dependence of the relaxation time and have calculated the attenuation coefficient in the absence and presence of dc fields respectively. Both of these investigations use the Cohen, Harrison and Harrison (CHH) model[6] of the collision term. In a recent paper, Sharma and Kaw[7] have pointed out that CHH model of the collision term is invalid for the energy dependent relaxation time for the simple reason that CHH model does not conserve the number of particles - a condition which must always be satisfied. Using an appropriate model of the collision term, Sharma and Kaw have calculated the absorption coefficient of an acoustic wave for the case of acoustic phonon scattering. Their results show that in some cases the use of appropriate model of the collision term leads to significant changes in the value of absorption coefficient.

Chapter II deals with the theory of attenuation and amplification of acoustic waves in presence of dc fields in semiconductors with energy dependent relaxation times. This chapter is further divided into two sections. In section A, a theory for the attenuation and amplification of acoustic waves in semiconductors with dominant acoustic phonon scattering has been given. In contrast to the earlier works, we use the collision term given by Sharma and Kaw[7] to solve the Boltzmann equation. The effect of the dc field on the distribution function has been taken into account following the work of Yamashita and Watanabe[8]. The theory for the attenuation/amplification of acoustic waves given in section A of chapter I, is applicable to the case of lightly doped semiconductors where the acoustic phonon scattering is the dominant scattering mechanism. In section B, a theory for the attenuation and amplification of acoustic waves in highly doped semiconductors is given. Here ionized impurity scattering is considered as the dominant electron scattering and Maxwellian distribution as the electron velocity distribution function.

Part II of the proposed thesis deals with the nonlinear aspects of acousto-electric effect i.e. second harmonic generation of an acoustic wave and convolution of surface acoustic waves and has been divided into three chapters.

In chapter III, an elementary theory is developed to study the acoustic wave second harmonic generation in piezoelectric as well as nonpiezoelectric semiconductors. A comparative study of the role of deformation potential and piezoelectric scatterings has also been made.

In chapter IV, we develop a kinetic theory for the second harmonic generation of an acoustic wave for piezoelectric semiconductors with acoustic phonon scattering as the dominant scattering. In contrast to earlier work[9], we use the collision term given by Sharma and Kaw[7] to solve the Boltzmann transfer equation. The results of the present theory show that in the range of low frequencies ($q\ell << 1$), the values of the second harmonic yield (i.e. the ratio of the acoustic flux associated with the second harmonic to the square of the acoustic flux associated with the fundamental acoustic wave) are appreciably different to those obtained with the CHH model while in the range of high frequencies ($q\ell \gg 1$), the values of the second harmonic yield obtained from the two models are in vicinity.

Chapter V, of the proposed thesis deals with the theory of convolution of surface waves in semiconductors. The process of convolution can be performed via the nonlinear interactions of two oppositely directed surface acoustic waves[10]. It is shown that for materials having large dielectric constants, the convolved signal output is much greater than in materials exhibiting piezoelectricity.

The proposed thesis may be divided into five chapters whose brief summaries are as follows:-

Chapter-I: Amplification of Acoustic Waves Due to External Temperature Gradient in Piezoelectric Semiconductors

In this chapter, we propose that application of an external temperature gradient can lead to the amplification of acoustic wave.

Chapter-II: Attenuation and Amplification of Acoustic Waves in Presence of DC Fields in Non-Piezoelectric Semiconductors considering Energy Dependent Relaxation Times

Part-A: Using the collision model suggested by Sharma and Kaw for energy dependent relaxation times, we solve the Boltzmann transport equation for anisotropic part of the distribution function in the presence of an acoustic wave and a dc field of arbitrary strength and calculate the attenuation/amplification coefficient in a nondegenerate semiconductor. The scattering of electron with acoustic phonon has been taken as the sole mechanism of scattering. The effect of the dc field on the isotropic part has been taken into account by using the Yamashita and Watanabe's distribution. Our results show that for $q\ell \ll 1$, the value of absorption coefficient are appreciably different from those obtained by using well known Cohen-Harrison-Harrison model while for $q\ell \gg 1$, no significant difference is observed in the values of the absorption coefficient obtained from two models of the collision term.

<u>Part B</u>: Using the Boltzmann transfer equation approach with appropriate collision term suggested by Sharma and Kaw, we obtain an expression for attenuation/amplification coefficient of an acoustic wave in a nondegenerate semiconductor in the presence of a dc electric field. The ionized impurity scattering has been taken as the dominant scattering mechanism. A comparison of our results with those obtained by using the CHH model is also made.

Chapter-III: Acoustic Harmonic Generation in Semiconductors

A phenomenological theory is developed to study the acoustic wave second harmonic generation in piezoelectric as well as nonpiezoelectric semiconductors, and derive the optimum conditions for maximum harmonic generation. The results show that second harmonic flux is maximum at higher frequencies in nonpiezoelectric semiconductors, and at lower frequencies in semiconductors exhibiting both piezoelectricity and deformation potential, as compared to the case of pure piezoelectric materials, while it is minimum at $v_d = v_s$ for both the coupling mechanisms.

Chapter-IV: Acoustic Harmonic Generation in Piezoelectric Semiconductors with Energy Dependent Relaxation Times

In this chapter, we study the second harmonic generation in nondegenerate semiconductors with energy dependent relaxation times in the presence of an acoustic wave. The interaction of electrons with the acoustic wave is taken into account through piezoelectric coupling. In contrast to earlier works, we use a modified collision term, given by Sharma and Kaw, valid for energy dependent relaxation times to solve the Boltzmann equation. Our calculations show that the values of the second harmonic yield for various values of $q\ell$ differ significantly for $q\ell \ll 1$ and are closer for $q\ell \gg 1$ with the corresponding values obtained by using Cohen-Harrison-Harrison collision model. Further, the second harmonic yield has a maximum at $q\ell \gg 1$.

Chapter-V: Convolution of Surface Waves in Materials with Strain Dependent Dielectric Constants

Convolution of surface waves in materials with strain dependent dielectric constants (e.g. Barium Titanate) is shown to be much larger as compared to piezoelectric materials. A phenomenological theory is developed to derive the analytical expressions for the convolved signal output, V_C. It is found to differ considerably with that for piezoelectric materials as regards the dependence of V_C on frequency of acoustic waves, mobility and strength of dc electric field.

The above mentioned work has resulted in the following publications:-

1. Amplification of acoustic waves due to external temperature gradient in semiconductors, J.Appl.Phys. 45, 4656 (1974).
2. Attenuation and Amplification of acoustic waves in the presence of dc fields in semiconductors with energy dependent relaxation times (Communicated, 1975).
3. Absorption of acoustic waves in semiconductors with dominant ionized impurity scattering (communicated, 1975).
4. Acoustic Harmonic generation in nondegenerate semiconductors, Acustica 32, 329 (1975).

5. Acoustic harmonic generation in piezoelectric semiconductors with energy dependent relaxation times (Communicated, 1975).
6. Convolution of surface waves in materials with strain dependent dielectric constants, J.Phys.D: Appl.Phys. 8,   (1975).

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. On the contribution of nonparabolicity to the longitudinal magneto-resistance, Phys.Stat.Sol.(a) 22, K195 (1974).
2. Stimulated electron-phonon-photon interactions in nondegenerate semiconductors considering energy-dependent relaxation time, J.Appl.Phys. 46, 846 (1975).

CONTENTS

PART-I

PART-II