

**INTERACTION OF HIGH FIELDS WITH POLAR
SEMICONDUCTORS AND DIELECTRICS**

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REPRINTS AND ABSTRACTS OF RESEARCH PUBLICATIONS

PREFACE

The interaction of strong electric, magnetic and electromagnetic fields with polar semiconductors and dielectrics has been widely investigated in recent years. Many aspects of nonequilibrium carrier phenomena (e.g. hot electron effects, Bulk Negative Differential Conductivity (BNDC) etc.), numerous quantum magnetic field effects and the propagation of strong electromagnetic waves have recently received a great deal of attention. This thesis presents a theoretical investigation of some aspects of hot electron effects in III-V and II-VI compounds, the quantum magnetic field effects in a nonparabolic semiconductor and the interaction of strong electromagnetic waves with dielectrics and semiconductors. The thesis has been divided into three parts.

PART 'A'

This part is concerned with the investigation of high electric field effects in polar semiconductors. From a theoretical point of view these investigations lead to a better understanding of the electron-lattice interaction and more precise knowledge of various semiconductor parameters viz. the coupling constants for the different modes of el-lattice interactions, the band structure in the high energy and normally inaccessible regions etc. Further such studies find application in a host of interesting effects and devices e.g. Gunn effect, anisotropy of microwave conductivity etc. Thus the study of high field effects is of considerable practical interest. In this part of the thesis we have been concerned

with only those high field phenomena which are directly due to an increase in the average energy of the carriers; the carrier density and the phonon population has therefore been assumed to be unaffected by the high fields. Thus some phenomena e.g. impact ionization, avalanche, acoustic flux generation have been omitted. Further since theoretical arguments and experimental evidence tend to favour solving the Boltzmann equation as a superior technique as compared to the effective electron temperature models, we shall use the Boltzmann Equation as the starting point for our analyses.

The following is a chapterwise summary of the work presented in this part:

Chapter I

The inclusion of Pauli's exclusion principle in the framework of the Boltzmann Equation Solution approach (BES) has been achieved only recently. However, the lack of a rigorous theory which would include degeneracy along with the exact electronic wave functions motivated us to derive, in section 1, a hot electron distribution function for arbitrarily degenerate, nonparabolic, polar semiconductors subjected to a nonquantizing dc magnetic field arbitrarily oriented with the dc heating electric field at high lattice temperatures ($T > \Theta$). The analysis incorporates degeneracy along with the exact wave functions for electrons which interact with the lattice through dominant screened polar optical mode of scattering. Calculations for a few important isothermal Galvano Thermomagnetic Transport Coefficients

(GTMC) (e.g. electrical and thermal conductivities, Hall, Nernst, Ettinghausen-Nernst coefficients etc.) have been performed for the typical case of a n-InSb sample for both nondegenerate and degenerate samples in order to focus attention on the consequences of degeneracy. Increasing degeneracy makes the distribution hotter and leads to a reversal of the electric field dependence of the Ettinghausen-Nernst coefficient; the rest of the GTMC exhibit the same qualitative behaviour for all values of the electric field. The influence of a nonquantizing magnetic field on the GTMC is consistent with its cooling action.

It is well known that the orthonormal expansion of the distribution function of hot electrons interacting predominantly with polar optical phonons converges rather slowly. This casts doubt on the standard procedure of truncating the series after the first two terms. In section 2 therefore, we examine the convergence of the orthonormal expansion more critically by retaining the first four terms of the series. We conclude that degeneracy makes the expansion converge more rapidly and that the inclusion of higher order terms opposes the cooling effect of nonparabolicity. The above results should find application in the interpretation of hot electron experiments above the Debye temperature and also under conditions when the distribution starts diverging from the nearly isotropic nature to the elongated distribution; lack of experimental results, however, deprives us of the chance of making any explicit comparison.

The marked anisotropy of the electron-polar phonon scattering, which leads to a peaking of the distribution, has prompted us to make a comparative study of the maximum and minimum anisotropy approximations. This investigation, which was motivated by the lack of a suitable theoretical approach for the above situation, is expected to provide bounds on the values of the various transport coefficients.

Chapter II

The interest in piezoelectric semiconductors has been recently revived due to the numerous acousto-electric instabilities associated with them. Hence a more critical investigation of the form of the distribution function before the onset of the instabilities has been carried out. The higher order terms in the BES are shown to contribute significantly to the distribution function for both parabolic and nonparabolic conduction bands. The breakdown field for parabolic conduction bands is, however, lowered whereas for a hyperbolic band no runaway is predicted. A closer scrutiny of the problem for electrons contained in a parabolic conduction band and interacting with the lattice only through the piezoelectric mode of scattering, however, revealed the electron distribution function to be inherently unstable at all values of the applied electric field; the earlier investigations had predicted a normalisable distribution below a certain critical field. As experiments have established that for piezoelectric semiconductors no breakdown occurs without the generation of carriers, it is concluded that for parabolic semiconductors other scattering

mechanisms, such as the deformation potential scattering, must be invoked to prevent runaway whereas for nonparabolic semiconductors piezoelectric scattering alone is sufficient to contain the carriers.

Chapter III

Recently it has been pointed out that the different types of instabilities in semiconductors e.g. the N and S types, are intimately connected. Of the two, the N-type BNDC leading to Gunn oscillations has attracted a tremendous amount of attention and the domain dynamics and current-voltage characteristics have been analyzed in great detail. Since a magnetic field has a cooling effect one normally anticipates an increase in the threshold field for Gunn effect. But on the contrary, an appreciable reduction in the value of the threshold field with the applied magnetic field has recently been observed in n-InSb at 77°K. This tends to cast doubt on the validity of the intervalley transfer mechanism for the occurrence of BNDC. We have, however, demonstrated that the simultaneous presence of the cooling and geometrical magnetoresistance effects satisfactorily accounts for the apparently inconsistent negative magnetic field coefficient of the threshold field.

PART 'B'

The work in part A is concerned with the behaviour of electrons in the presence of arbitrarily oriented strong electric and nonquantizing magnetic fields. Some of the most

fascinating magnetic field effects e.g. the Shubnikov-DeHaas and DeHaas-Van Alphen oscillations, magnetophonon oscillations, longitudinal effects etc. occur only when the magnetic field is strong enough ($\hbar\omega_c \gtrsim kT$) to quantize the conduction band. In the quantum limit even an isotropic material exhibits longitudinal effects such as longitudinal magnetoresistance (LMR). The occurrence of LMR in isotropic materials has been explained as being due to the magnetic field dependence of the relaxation time. However, the implications of the magnetic field dependent effective mass of carriers in a nonparabolic semiconductor subjected to quantum magnetic fields have not been completely realized. This part of the thesis therefore, deals with the various consequences of the magnetic field dependence of the effective mass; the analyses assume the absence of carrier freeze-out.

Chapter IV

In particular we have demonstrated in section 1 that this magnetic field dependence of the effective mass can, by itself, lead to a nonzero LMR even if the relaxation time is assumed to be constant. In general nonparabolicity causes an enhancement in the LMR for both degenerate and nondegenerate samples along with an increased sensitivity to the magnetic field as compared to a parabolic conduction band. This is expected to be a significant mechanism of LMR for many III-V compounds viz. InSb, InAs etc. which have a markedly non-parabolic conduction band.

In section 2 of this chapter we propose the cyclotron

resonance determination of the magnetic field dependent effective mass of carriers in nonparabolic conduction bands subjected to magnetic fields in the extreme quantum limit ($\hbar\omega_c \gg kT$) as an additional method for estimating the effective mass band gap. This method is expected to be useful for large spin-orbit splitting, narrow band gap ($\Delta \gg \epsilon_g$), nonparabolic semiconductors at low lattice temperatures ($kT \ll \epsilon_g$).

The last section discusses the focusing of low intensity microwaves in nonparabolic semiconductors due to the application of an inhomogeneous quantum field with appropriate spatial dependence. The inhomogeneity of the quantum magnetic field gives rise to an inhomogeneous effective mass which, in turn, enforces a spatial dependence on the effective dielectric constant. An appropriate choice of the magnetic field configuration leads to the formation of a SELFOC or duct like medium which causes a focusing of the microwaves.

PART 'C'

Hot electron conditions in semiconductors are usually produced by applying short duration, high voltage pulses to the sample which must be specially prepared to avoid injection at the contacts. This method, however, fails when the current-voltage characteristics exhibit a BNDC region and recourse has to be made to heating the sample electromagnetically. This method has an inherent additional advantage of avoiding injection and is feasible due to the availability of strong

radiation sources. Further the effect of strong electromagnetic fields on various kinetic effects is expected to yield valuable information about semiconductor parameters, especially for III-V and II-VI compounds whose free carrier contribution to the nonlinearity at microwaves dominates that due to the polarization of the background lattice. While studying the above mentioned problems one has to determine the conduction current due to the propagating electromagnetic wave at one stage or the other and the most consistent approach, therefore, is by means of an electron distribution function.

Chapter V

This motivated us to evaluate arbitrarily degenerate, hot electron distribution functions for realistic nonparabolic but isotropic band structures by solving the time dependent Boltzmann equation in the presence of arbitrarily oriented strong electromagnetic and dc magnetic fields for various appropriate combinations of carrier - lattice interactions corresponding to different temperature ranges. It is shown that the distribution functions depend not only on the electromagnetic field strength but also on how the electromagnetic energy is divided into the two modes. The treatment is fairly general and should find application in the interpretation of various kinetic effects in the presence of strong electromagnetic waves for most of the semiconductors.

Chapter VI

For strong electromagnetic waves in the optical region,

the nonlinear polarisation of the background lattice, which dominates over the free carrier nonlinearity, provides the coupling constant for a host of optical parametric interactions e.g. harmonic generation, parametric oscillations etc., which have found extensive practical applications. Usually harmonics or parametric oscillation, for testing purposes, are generated in nonlinear, birefringent crystals by a loosely focused, low power, CW laser beam. The accompanying low conversion efficiency lends paramount importance to the phase matching requirement.

Various inherent and induced inhomogeneities e.g. stratifications, striae, self induced thermal effects etc., however, introduce a phase mismatch and hence degrade the sample. We have, therefore, carried out a detailed investigation of the relative importance and influence of the above mentioned sources of phase mismatch on the second harmonic generation in nonlinear crystals choosing Barium (Ba₂NaNb₅O₁₅) as a specific example. An interesting outcome of the analysis is the prediction of two phase matching temperatures when striae and thermal effects occur simultaneously. The results should be useful in weeding out pathological crystals especially those having a large amount of stratifications.

The thesis is partly based on the following publications.

1. Hot Carrier Distribution Function in Degenerate Nonparabolic Semiconductors, Phys.Rev. B3, 2619 (1971).

2. Distribution Function of Degenerate Hot-Carriers in Nonparabolic Semiconductors: E.M.Heating, Phys.Stat.Sol.(a) 6, 395 (1971).
3. Effect of Magnetic Field on Gunn Effect in n-InSb, Solid State Comm. 9, 1877 (1971).
4. Validity of Hot Electron Distribution Function for Piezoelectric Scattering, Phys.Stat.Sol.(b), 48, 823 (1971).
5. Non-normalizability of the Hot Electron Distribution Function for Piezoelectric Scattering, Phys.Stat. Sol.(b) 50, K1 (1972).
6. Degeneracy and Screening Effects in the Transport Coefficients of n-type InSb at High Temperatures, Phys.Rev. B6, 2414 (1972).
7. Modified form of Energy Distribution Function for Hot-Carriers in Polar Semiconductors: Inclusion of Higher Order Terms, Phys.Rev.B (Accepted 1972).
8. Contribution of Nonparabolicity to Longitudinal Magneto-resistance at Quantum Magnetic Fields, Phys.Rev.Letts. 29, 272 (1972).
9. Focusing of E.M.Waves in Plasmas by Inhomogeneous Magnetic Fields, Appl.Phys.Letts. (In Press).
10. Optical Second Harmonic Generation in Crystal: Influence of Inhomogeneities and Self-Induced Thermal Effects, (Communicated 1972).
11. A Comparative Study of the Maximum and Minimum Anisotropy Approaches for Hot Electrons in Polar Semiconductors at High Temperatures, (Communicated 1972).
12. A New Proposal for the Focusing of Microwaves in Nonparabolic Semiconductors: Application of an Inhomogeneous Quantum Magnetic Field, (Communicated 1972).
13. Longitudinal Magnetoresistance in Nonparabolic Semiconductors in the Quantum Limit(Communicated 1972).
14. An Additional Method for the Determination of Band Gap in Nonparabolic Semiconductors (Communicated 1972).

PART 'A'

HIGH ELECTRIC FIELD EFFECTS IN POLAR SEMICONDUCTORS

The interaction of strong electric fields with polar semiconductors has been extensively investigated in recent years. Many aspects of nonequilibrium carrier phenomena e.g. hot electron effects, bulk negative differential conductivities etc. have been studied. From the theoretical point of view these investigations lead to a better understanding of the electron-lattice interaction & more precise knowledge of various semiconductor parameters (viz. the coupling constants for the different modes of electron-lattice interactions, the band structure in the high energy and the normally inaccessible regions etc.). Further such studies find application in a host of interesting effects and devices e.g. Gunn effect, anisotropy of microwave conductivity etc. Thus the study of high field effects is of considerable practical importance. In this part of the thesis we shall be concerned with only those high field phenomena which are directly due to an increase in the average energy of the carriers; the carrier concentration and the phonon population and distribution will therefore be assumed unaffected by the electric field thus leaving out some effects e.g. impact ionisation, avalanche, acoustic flux generation etc. As theoretical arguments and experimental evidence tend to favour solving the Boltzmann equation as a superior technique, compared to the effective electron temperature models, we shall use the Boltzmann Equation Solution approach (BES) for most of our analyses.

The first chapter is concerned with the hot electron

transport in polar semiconductors at high lattice temperatures. The implications of degeneracy and screening of the electron-polar phonon interaction have been investigated extensively in section 1. The marked anisotropy and inelasticity of the el-polar phonon scattering motivated us to study the effect of higher order terms in the spherical harmonics expansion of the distribution function in section 2. The peaking of the distribution for dominant el-polar phonon scattering prompted us to make a comparative study of the maximum and minimum anisotropy approximations so as to obtain the bounds on the various transport coefficients; this constitutes the last section of this chapter.

In chapter II we have investigated the validity of the distribution function for carriers interacting with the lattice only through the piezoelectric mode of scattering; the influence of higher order terms and the normalisability of the distribution function have been critically examined. This study was motivated by the renewed interest in piezoelectric semiconductors due to the numerous instabilities associated with them.

In the last chapter of this part we have studied the effect of a magnetic field on the Gunn effect threshold; in particular, the simultaneous presence of the bulk cooling and the geometric magnetoresistance effects has been shown to satisfactorily account for the apparently inconsistent negative magnetic field coefficient of the threshold field.