HARMONIC GENERATION AND OTHER TRANSPORT PHENOMENA IN SEMICONDUCTORS

Satish Kumar Sharma

Thesis submitted to Indian Institute of Technology, Delhi, for partial fulfilment of the Degree of
Doctor of Philosophy
1968

ACKNOWLEDGEMENTS

The author wishes to express his deep sense of gratitude to Professor M.S. Sodha for valuable guidance, kind encouragement and inspiration without which the present work would not have been possible.

The author is greatly indebted to Dr. P.K. Kaw for his helpful suggestions and discussions at various stages of this work. The author also wishes to express his sincere thanks to Professor S.C. Jain, Professor P.K.Katti and his colleagues for their encouragement and help that was extended to him.

The author is thankful to the Council of Scientific and Industrial Research (India) and also to Environmental Science Services Administration (U.S.A) for financial assistance.

Satish Kumar Sharma.

PREFACE

The phenomenon of generation of harmonics in ionized gases and semiconductors has recently attracted the attention of many investigators because of its promise in the field of generation of electromagnetic waves of frequencies higher than that attainable by conventional generators.

While plasmas offer a higher conversion efficiency because of the lower collision frequency, the semiconductors offer much more ease of operation. Thus we can foresee devices using plasmas as well as semiconductors for harmonic generation. The high collision frequency can be considerably reduced by the application of low temperatures as has been pointed out by Sodha and Srivastava (1967) in their analysis of third harmonic generation in nondegenerate semiconductors. Members of our present group have suggested (Sodha and Kaw 1966a) the use of inhomogeneities in electron density and temperature and a D.C. electric field to enhance the efficiency of harmonic generation in plasmas.

In the present work, the author has investigated the harmonic generation in nondegenerate simple model semiconductors at low temperatures which have the gradients of electron density and temperature and in the presence of d.c. electric field. It is seen that the efficiency of harmonic generation is appreciable under typical operating conditions. The efficiency can in practice be increased by the use of higher gradients and d.c. electric fields, but the present second order theory will be no more applicable; however even under these conditions the present theory provides a qualitative guide line for the design of suitable experiments and hence may lead to work which may result in a useful device. The author has also extended the theory of third harmonic generation to degenerate semiconductors having non-parabolic energy bands; one of the promising material under this category is Indium Antimonide.

It may be pointed out here that in the above mentioned problems of harmonic generation, the author has only considered the nonlinearity due to the conduction of carriers; the other possible sources of nonlinearity which may also result in similar phenomena viz, the nonlinear dielectric polarizibility of the crystal have not been taken into account. Thus the present treatment is mainly limited to the microwave frequency range.

The author has also been active in the related field of transport phenomena in simple model degenerate covalent semiconductors and nondegenerate piezoelectric semiconductors (for example CdS). The dependence of various transport properties on the impurity parameter has been investigated for degenerate semiconductors. For nondegenerate semiconductors, the Boltzmann's transfer equation for carriers has been solved in the presence of high d.c. electric field and a d.c. magnetic field, taking into account both the deformation potential scattering and piezoelectric scattering. The study of such transport phenomena in semiconductors, which involves the measurement of various transport coefficients may give very useful information about many important parameters of semiconductors viz. electron density, impurity concentration and chemical potential etc., when used in conjunction with the theory developed.

The author has also studied the second order non-linear thermal diffusion of electrons in plasmas and semiconductors. The earlier theory of Sodha and Srivastava (1966) has been extended to include the effect of magnetic field on second order thermal diffusion.

Another phenomenon which involves the movement of carriers is electron emission. The author has investigated the problem of Schottky emission from spherical particles having a negative charge. This investigation is extremely useful in the field of colloidal plasmas where the electron density and the collision frequency in a gas are affected by the presence of dust of a suitable material.

The thesis has been divided in seven chapters, whose titles and summaries are given below:

Chapter I: Generation of Second Harmonic and Sum and Difference Frequencies in Nondegenerate Semiconductors in the Presence of D.C. Electric Fields:

It is well known that when a semiconductor is subjected to a moderately strong electric field, its response to the field becomes nonlinear. If the applied electric field is alternating, then the nonlinear effects in semiconductor lead to the generation of harmonic components in the current density. Similarly if two alternating electric fields of different frequencies are simultaneously applied to the semiconductor, the nonlinear effects lead to the generation of combination frequency components in the current density. An important consequence of the generation of these higher order components in the current density, is the generation of harmonics and combination frequency waves, when two moderately strong electromagnetic waves of different frequencies are propagating in the medium.

The first significant theoretical analysis of the generation of harmonics appears to have been made by Margenau and Hartman (1948) for the case of plasmas in which the time dependence of the various parts of the distribution function of electron velocities was investigated in the presence of an alternating electric field. An explicit expression for the third harmonic component of the current density was obtained by Rosen (1961). Since then many workers have dealt with various aspects of harmonic generation in plasmas (Sodha and Palumbo 1963, Krenz 1965, Wetzel 1961, Vilenski 1952, 1954, Chiyoda 1965, Sodha and Kaw 1966a,b). In semiconductors the first analytical treatment for the generation of third harmonic component in the current density was given by Paranjape (1961). Later Nag and Guha (1965), Das (1965) and Sodha and Srivastava (1967) have also studied the problem of third harmonic generation in semiconductors.

In Chapter I, the author (Sodha et al,1968a) has investigated the generation of second harmonic and sum and difference frequencies in semiconductors in the presence of a d.c. electric field. Using the rigorous kinetic theory techniques which involve the use of Boltzmann's transfer equation,explicit expressions for second harmonic and sum and difference frequency components in the current density in a simple model nondegenerate semiconductor are obtained. Electron scattering due to acoustic mode of lattice vibrations as well as ionized impurities have been taken into account. An interesting feature of this analysis is that second harmonic and sum and difference frequency components in the current density are directly proportional to the magnitude of applied d.c. field and thus, by adjusting d.c. field to a large value, the harmonic yield in the current density can be considerably increased. The expressions for the current density components along with the wave equation and the appropriate boundary conditions are used to obtain expressions for the amplitudes of second harmonic and sum and difference frequency waves in the reflected as well as transmitted components. For a typical case of germanium slab at 77^{o}K and other parameters the amplitudes of second harmonic wave in the reflected and transmitted components have been calculated.

Chapter II: Generation of Second Harmonic in Inhomogeneous Non-degenerate Semiconductors at Low Temperatures:

In this chapter the author (Sodha et al, 1968b) has derived an explicit expression for second harmonic component in the current density in an inhomogeneous nondegenerate semiconductor by solving the Boltzmann's transfer equation for carriers; scattering by ionized impurities is considered as the dominant scattering mechanism. It is seen that the second harmonic component in the current density is directly proportional to the gradients of electron density and temperature and thus, by increasing the values of gradients of electron density and temperature, the second harmonic component in the current density can be substantially increased. The expression for the second harmonic component in the current density is substituted in the wave equation and the resulting nonlinear differential equations have been solved to obtain expressions for the amplitude of second harmonic wave in the reflected and transmitted components. For an appreciation of the magnitude of the generated second harmonic wave some numerical values for typical cases have been presented.

Chapter III: Generation of Third Harmonic in Nonparabolic n-type Degenerate Semiconductors at Low Temperatures:

In Chapter III, the author (Sodha and Sharma 1968c) has given a theory for the generation of third harmonic in low gap semiconductors (viz. InSb) which are characterized by degeneracy and nonparabolic energy bands. In this analysis the author has investigated the magnitude of the third harmonic component in the current density by solving the Boltzmann's transfer equation for carrier wave vectors, using the wave vector dependence of electron energy derived by Kane (1957). The explicit expression for the amplitude of third harmonic component in the reflected wave is obtained when a strong microwave is normally incident on a free space-semiconductor interface. Electron scattering due to ionized impurities is considered to be the dominant scattering mechanism. This is justified by the recent work of Kinch (1966). Numerical values for typical cases have also been calculated.

Chapter IV: Some Transport Coefficients of Degenerate Simple Model Semiconductors:

In this chapter the author (Sharma 1967a,b) has derived expressions for some transport coefficients of degenerate semiconductors viz. Lorentz number, Hall coefficient, Hall mobility, coefficient of magnetoresistance and absolute thermoelectric power, considering the simultaneous occurrence of acoustic phonon scattering and ionized impurity scattering.

The variation of these transport coefficients with the impurity parameter has been investigated.

Chapter V: Some Transport Coefficients in CdS:

In this chapter the author (Sodha and Sharma 1968d) has analytically investigated the dependence of Hall coefficient, Hall mobility and coefficient of magnetoresistance in CdS on scattering parameter, applied electric field and the magnetic field. Assuming a simple model of band structure the author has solved the Boltzmann's transfer equation for carriers to obtain explicit expressions of the distribution function of electron velocities and transport coefficients which are valid for all values of electric and magnetic field strengths. Scattering of electrons due to piezoelectric potential and deformation potential has been considered. The variation of the transport coefficients with various parameters has been graphically illustrated.

Chapter VI: Higher Order Thermal Diffusion of Electrons in Ionized Gases and Semiconductors:

In this chapter the author (Sharma and Kaw 1967,1968) has analytically investigated the nonlinear and second order thermal diffusion of electrons in ionized gases, using the techniques of the kinetic theory; the temperature dependence of the electron density has been taken into account in contrast with the earlier work (Sodha and Srivastava 1966).

Chapter VII: Electron Recombination and Thermionic Emission in Negatively Charged Solid Particles:

In this chapter the author (Sodha and Sharma, 1967) has calculated the coefficient of recombination of electrons with negatively charged solid particles and the rate of thermionic emission from such particles by using an appropriate expression for the potential energy of electrons near the surface of the particles instead of the idealized relationship used in an earlier paper by Sodha (1963). The results are discussed together with relevant numerical data.

All of this work has been done under the effective supervision of Professor M.S. Sodha and therefore many of the papers published on the basis of this work are in joint authorship. The entire work has resulted in following publications:

(i) Generation of second harmonic and sum and difference frequency in semiconductors at low temperatures. M.S. Sodha, G.P. Gupta and S. Sharma. Jr. of Physical Soc. Japan, 1968 Vol. 25, No. 3, 754.

(ii) Nonlinear second harmonic generation in inhomogeneous semiconductors at low temperatures. M.S. Sodha, S. Sharma and P.K. Kaw, Jr. Phys. C (Proc. Phys. Soc.) 1968 1, 1128.

(iii) Third harmonic generation in nonparabolic semiconductors at low temperatures. M.S. Sodha and S. Sharma 1968 (communicated).

(iv) Some transport coefficients in n-type degenerate semiconductors, S. Sharma, Canad. Jr. of Phys. 1967, 45, 2385.

(v) Absolute thermoelectric power of degenerate semiconductors, S. Sharma, Canad. Jr. of Phys. 45,4119.

(vi) Some transport coefficients in Cadmium Sulphide, M.S. Sodha and S. Sharma, Phys. Stat. Solid. (in press).

(vii) a. Nonlinear and second order thermal diffusion of electrons in ionized gases, S. Sharma and P.K. Kaw, Z. Physik, 1967, 203, 330.

b. Higher order thermal diffusion of electron in ionized gases, S. Sharma and P.K. Kaw, Indian Jr. Pure and Applied Physics, 1968 (in press).

(viii) Electron recombination and thermionic emission in negatively charged solid particles, M.S. Sodha and S. Sharma, Brit. Jr. App. Phys., 1967, 18,1127.

BIBLIOGRAPHY

Chiyoda, K., 1965, J. Phys. Soc. Japan, 20, 290.

Das, P., 1965, Phys. Rev., 138, A590.

Kane, E.O., 1957, Jr. Phys. Chem. Solids, 1, 249.

Kinch, M.A., 1966, Proc. Phys. Soc. 88, 1257.

Krenz, J.H., 1965, Phys. Fluids, 8, 1871.

Margenau, H. and Hartman, L.M., 1948, Phys. Rev., 73, 309.

Nag, B.R., Guha, S., 1965, Brit. Jr. Ap. Phys., 16, 1461.

Paranjape, B.V., 1961, Phys. Rev., 122, 1372.

Rosen, P., 1961, Phys. Fluids, 4, 341.

Sharma, S., 1967a, Cand. Jr. Phys., 45, 2385.

Sharma, S., 1967b, Cand. Jr. Phys., 45, 4119.

Sharma, S. and Kaw, P.K., 1967c, Z. Physik, 203, 330.

Sharma, S. and Kaw, P.K., 1968, Ind. J. P.A.Phys.(In Press).

Sodha, M.S., 1963, Brit. Jr. App. Phys., 14, 172.

Sodha, M.S. and Kaw, P.K., 1966a, J. Phys. Soc. Japan, 21, No. 1, 134.

Sodha, M.S. and Kaw, P.K., 1966b, J. Phys. Soc. Japan, 21, No. 12, 2684.

Sodha, M.S. and Palumbo, C.J., 1964, Cand. Jr. Phys., 42, 1236.

Sodha, M.S. and Sharma, S., 1967d, Brit. Jr. App. Phys., 18, 1127.

Sodha, M.S., Gupta, G.P. and Sharma, S., 1968a, J. Phys. Soc. Japan, 25, No. 12, 754.

Sodha, M.S., Sharma, S. and Kaw, P.K., 1968b, Jr. Phys. C (Proc. Phy. Soc.), 1, 1128.

Sodha, M.S. and Sharma, S., 1968c, Phys. Stat. Solidi, (In Press).

Sodha, M.S. and Sharma, S., 1968d (Communicated).

Sodha, M.S. and Srivastava, H.K., 1966, Z. Physik, 195, 13.

Sodha, M.S. and Srivastava, H.K., 1967, Proc.Phys.Soc., 90, 435.

Vilenski, I.M., 1952, Zh.Eksper,Teor.Fiz., 22, 544.

Vilenski, I.M., 1954, Zh.Eksper,Teor.Fiz., 26, 42.

Wetzel, L., 1961, Phys. Rev., 123, 722.

TABLE OF CONTENTS