CHAPTER I

Basic Concept of Physics of Plasma in Semiconductors
CHAPTER 1

1.1 INTRODUCTION

The present chapter deals with the basic concept of the physics of plasma in solids (semiconductors). It serves as an introduction for the next chapters.

The term "plasma" denotes quasineutral ionized gas. Quasineutrality means that the number of positive charges is equal on the average to that of negative ones, in sufficiently large volume and over sufficiently large time intervals.

The basic special property of the plasma which makes it possible to interpret it as a special state of matter is the collective response of the plasma particles to electromagnetic perturbations. The words "collective response of a system" mean perturbation of some physical quantity (the charge density, the electric or magnetic field strength, the particle number density). This perturbation is assumed to be macroscopic in the sense that its geometrical dimensions which will be described by the wave lengths ($\lambda$) are at any rate much greater than the average distance between particles in the plasma

$$\lambda \ll n_o^{-1/3}$$  \hspace{1cm} (1.1)

While in a gas consisting of neutral particles where the inter-particle interaction is caused by pair collisions collective response to a perturbation represents gas density compression-expansion (i.e., acoustical) waves, in a gas of charged particles, plasma, many other types of waves appear, in addition to the acoustical ones, which are produced and accompanied by electric and magnetic fields. The action of fields and particles in the plasma is
self-consistent, in the sense that the motion and the regrouping of charged particles in the plasma product fields, and the latter lead to the motion and the regrouping of plasma particles,

Plasma in semiconductors. The concept of plasma in a solid (semiconductor) is used to describe the collective response of a quasineutral system consisting of free charge carriers of two signs and ionized impurity atoms, also of two signs, to electromagnetic perturbations.

The medium for charge carriers in solids is characterized by a high value of dielectric constant, which makes it possible to ionize atoms easily and to realize the plasma state even at very low temperatures. The ions of such plasma are rigidly connected, with the lattice. The mobile charges, electrons and holes, subjected to the action of the electric field, move freely over the crystal, without violating the neutrality conditions. Each free electron corresponds to a positively charged ion-donor or a hole. Each hole corresponds to a negatively charged ion-acceptor or an electron. By analogy with the terminology of semiconductors, the plasma existing in them is called either electron or hole or intrinsic plasma. The plasma containing one kind of mobile carriers is also frequently called stationary or "charged". The last term cannot be regarded as appropriate since the presence of the compensating charge of the opposite sign is always assumed. When a plasma contains more than one kind of mobile particles, it is called multicomponent. Other name for the intrinsic plasma are "compensated", "neutral" and "mobile".

Numerous collections of electrons with defects and vibrations of the crystalline lattice are also responsible for the specific character of plasma in
semiconductors, since the nature of such collisions depends on the electron energy and momentum, and in the non-equilibrium state the energy distribution of electrons may differ substantially from the boltzmann one.

An important peculiar feature of the plasma in semiconductors is also associated with the possibility of varying its parameters within very broad limits through various external influences and the technology of the crystal production. For instance, the concentration of mobile charges may be by several of magnitude greater than the maximal values which can be obtained in the gaseous plasma.

We are interested in the plasma collective response to electric, magnetic and other perturbations. This response is determined by the total effect of the microscopic processes in the plasma. Due to the statistical nature of motion of charged particles that perturb the field, the values of fields and currents in the plasma in each microscopic volume are, in general, also characterized by statistical dispersion. If the condition (1.1) is realized, however, one can use for the description of waves in the plasma volume the Maxwell equation for the average values of the electric and magnetic field in a medium (1).

\[
\text{rot } \vec{E} = -\frac{\partial}{\partial t} \vec{B}, \quad \text{rot } \vec{H} = \vec{J} + \frac{\varepsilon}{\mu} \vec{D},
\]

\[
\text{div } \vec{D} = \rho, \quad \text{div } \vec{B} = 0,
\]

(1.2)

In these expressions \( \vec{J} \) is the conduction current density, and \( \frac{\varepsilon}{\mu} \vec{D} \) is the density of the displacement current caused by polarization of the crystalline lattice.
The field equations (1.2) supplemented by equations for currents \( \mathbf{J} \) or charges \( \mathbf{p} \) which should include the plasma parameters as well as all kinds of forces that act on particles in the plasma from the complete system of equations allowing one to determine the plasma response to a given perturbation. It is practically impossible to find currents in the plasma from the equations of motion for each individual plasma particle. Therefore, in order to obtain the microscopic current in the plasma, various approximations are used. Consider the most important of them, namely, the single-particle approximation, the hydrodynamic approximation, the approximation of the kinetic equation.

The field of solid state plasma is a new discipline born between the realms of solid state physics and plasma physics. Plasma is described as a collection of charged particles of about equal number of positive and negative charges or collection of quasineutral charged particles, exhibiting collective behavior, for which the dimension of plasma should be very large compared to the Debye length; the number of particles in the Debye sphere should be much greater than one. Although the idea of Plasma in solid was used by Kroning (1943) and Kroning (1949) based on a phenomenological macroscopic theory, Pines (1955) and Nozieres and Pines (1958) gave the appropriate collective treatment of this problem in solids. The properties of gaseous plasma have been the subject of intensive study for many years. However, study of plasma effects in solids have been much more recent, with much of the significant progress comings from the work done in the last two to three decades. Many new solid state devices were discovered by understanding the effects in solids.
based on established plasma theory. What is striking is that the progress of experimental work on plasma in solids have been very rapid due to ready availability of pure materials. Thus it appears that the study of plasma in solid should prove fruitful both in providing tests of plasma theory and in enhancing knowledge of the properties of solids.

In solid state plasma, the study of the waves [1] instability have become important after the discovery that in the presence of magnetostatic field, [2] low frequency excitations can propagate through the non-compensated metals [3 to 5]. Since then a number of workers have observed experimentally the excitation of various collective modes in solids, [6 to 9]. The major practical interest in instabilities in solid state plasma is the possibility of adjusting the geometries of the system and the physical conditions to maximize their growth rate and thus derive from the plasma useful intensities of power in different frequency ranges. With the solid as a plasma source, the properties of the electrons, holes and interacting excitations are well known and controllable. The wide range of studies of instability in solid state plasmas has been discussed by a number of authors [9 to 19].

A number of facts have contributed to this growing interest in the subject of solid state physics. The realization that under appropriate conditions different types of waves ranging from audio frequencies to microwave frequencies have inducted much stimulus because of the fact that slow waves can propagate right through the bulk of solid conductors.
A plasma displays a variety of instabilities. An instability arises because of the existence of a source of free energy in the system. In a plasma, the source of free energy are the various currents set up in the equilibrium configuration because of the geometry of the set up and the background stationary fields. An uneven distribution of energy can also trigger instability. On the other hand, there is a class of instabilities in which the source of energy can be introduced through an external agency. By choosing appropriate field configuration, currents can be induced which can also lead of instability of a certain class of perturbations.

1.2 INSTABILITIES IN SOLID STATE PLASMA

There are two classes of physicists who are interested in the wave propagation and instabilities in solid state plasmas. Solid state physicists use them to obtain more detailed knowledge of the energy band structures of solid, where as the device physicists or engineers are interested in them primarily because the slow waves can be made to interact with externally applied waves as well as with other excitations in the solids. The engineers are particularly hopeful of using the knowledge of solid state plasma to make devices like amplifiers or oscillators. The potential attraction of solid state plasma devices are their small size, structural simplicity, cheapness, ruggedness, no cathode to heat in comparison to the conventional microwave devices such as travelling waves tubes and Klystrons which are larger and needs lot of power. The key to performing these functions lies in producing instabilities in the solid state plasma media.
The intense experimental and theoretical efforts of the past few years have yielded a bountiful return in our basic knowledge but in addition they have opened the ways to several classes of new devices with high efficiency and power in the different frequency regimes. The success on both the basic and applied plane offers promise for continuing useful result and increased knowledge for future work in these area.

The interaction between electrons and lattice vibrations is one of the fundamental interaction process in solid state plasma. [3] was 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 [3], [9], [15], [17 and 18], [20 to 32].

The fact that ‘electron-acoustic phonon’ interaction can lead to the amplification of acoustic waves by the application of a d.c. electric field has been commercially exploited for the fabrication of delay lines, acoustoelectric amplifiers, acoustoelectric oscillations, signal processing devices etc. Since acoustic waves are 105 times slower than 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 function. In addition, this electron-acoustic wave interaction also gives useful information about the band structure of material and scattering mechanisms.
Electron-acoustic wave interaction, in general, leads to three different effects in solid state plasma: (i) It results in the absorption of the wave, (ii) contributes to the value of the elastic constant and hence changes the acoustic wave velocity, and (iii) leads to the appearance of an electric field called "Acoustoelectric field". [20] first pointed that large parametric interaction between electron phonon in piezoelectric semiconductors. Later [21] demonstrated for the first time that it was possible to amplify acoustic waves in cadmium sulfide by the application of a d.c. electric field. A detailed theory for the amplification of acoustic wave in piezoelectric semiconductor have been carried out by [22]. Since then piezoelectric semiconductors have been extensively used to study the electron acoustic wave interaction and in fabrication of acoustoelectric and signal processing devices. All piezoelectric solids exhibit deformation potential and the coupling due to it increases with frequency and becomes comparable to that of piezoelectric coupling at frequencies in giga-hertz region. Thus, it seems necessary to include both types of couplings in the study of electron acoustic wave interactions in solids.

The investigations in solid state plasma are confined to the semiconducting plasma because these plasma are quite dilute compared to those found in metals. They occur in numerous variety and with range of parameters that far exceed those attainable in metals. Further, they are only solid state plasmas in which all parameters of interest; plasma frequency, Fermi-energy, phonon energy and band gap; can be made comparable. These combination of properties make the solid state plasma particularly a flexible...
medium for testing a wide range of plasma phenomena. Therefore, they have been extensively used to investigate the wave propagation and instabilities.

1.3 THEORETICAL APPROACH

In study of the electron acoustic wave interactions, in semi conducting plasma, there are three different theoretical approaches:

(i) Phenomenological approach
(ii) Boltzmann transport equation approach
(iii) Quantum mechanical approach

In the phenomenological approach we make an assumption that the Average velocity of the electron is equal to the drift velocity. This requires that the electron undergoes many collisions during the time when acoustic wave travels a distance of one wavelength. This approach is, therefore, limited to the low frequency region i.e. for \( k1 << 1 \) (where \( k \) is the wave number of the acoustic wave and \( 1 \) is the mean free path of the electrons). Nevertheless, the condition \( k1 >> 1 \) can be met over a wide range of frequencies of interest in semiconductors such as CDS, InSb etc. [33]. On the other hand, the Boltzmann equation is valid and widely used for the entire frequency range of acoustic wave while the quantum mechanical approach is suited to very high frequencies and for very strong electric and magnetic fields. Theoretical investigation on acoustic wave amplification predicts symmetrical behavior about the cross over field when electron drift velocity equals the velocity of sound. However, the observed experimental data are found to be asymmetric which needs modification of theory in terms of electron-hole mass ratio of charge carriers and nonlinearity in sample resistivity. Recently, [19] explained
the asymmetrical behavior observed in acousto-electric amplifiers in piezo as well as strain dependent dielectric constant materials in terms of effective electron-hole mass ratio of charge carriers and nonlinearity in sample resistivity. The asymmetry in gain caused by inhomogeneities at various operating frequency have been found effective in presence of traps.

The temperature dependence of ultrasonic wave amplifier have been studied by various workers [27 and 34], modifying the theory of [22]. However, in these studies role of effective electron-hole ratio, inhomogeneous conductivity and temperature dependent mobility and diffusion coefficient have not been examined to explain discrepancy in experimental observation and theoretical prediction. Therefore, a detail study is needed in the study of acoustoelectric effects. Further, earlier workers have been used phenomenological hydrodynamic approach theory, therefore the kinetic theory [36] is needed to generalize the theoretical prediction and provide a tool for investigating non-degenerate as well as degenerate semiconductors. Motivated by these considerations in the present thesis we have used kinetic approach as well as hydrodynamical approach in the case of non-degenerated piezoelectric semiconductors. The analysis of various acoustic wave interactions, in solid state plasma and resultant instabilities under a variety of configuration of the electric and magnetic field and the wave vector by various workers have been presented. Dispersion relation are derived of different types of acoustic wave in the medium using kinetic [36] and hydrodynamic model of plasma and the Maxwell's equations, The electrokinetic branch of the dispersion relation are
examined the propagation characteristic and the possibility of instabilities are investigated. The problems presented in this thesis may be divided as:

(i) Acoustic wave amplification due to phonon-;lasmon interaction in piezoelectric semiconducting plasma in the presence of an arbitrarily directed magnetic field.

(ii) Acoustic wave amplification in a transversely magnetized piezoelectric semiconductors in the presence of an a.c. electric field.

(iii) Acoustic wave amplification in nondegenerate piezoelectric as well as strain dependent dielectric constant materials in presence of traps.

(iv) Effect of temperature and magnetic on acousto electric amplifier field in presence of single trapping lever.

Ultrasonic modulation of microwave signals in the strain dependent dielectric constant materials.
REFERENCES


[31] DaY M. (Bose) and Ghosh S., (1990), Phys. stat. Sol. (b), 157, p. 159.


