1.1. Introduction:

In conductors and semiconductors the electrical conduction is due to the flow of electrons or holes. Ordinarily, these carriers undergo random motion inside the solid, making frequent collisions with the lattice, the impurities and amongst themselves. In thermal equilibrium condition, equal number of carriers, on the average, move with the same velocities in opposite directions, so that the net current flow in the solid is macroscopically nil and the energy distribution of the carriers in the momentum space is symmetric. On the application of an electric field, the carriers are accelerated in the direction of the field and gain energy from it. This gain in energy is lost to the lattice through collisions and, in the equilibrium condition, the energy distribution of the carriers can be represented by a symmetric component and a perturbation component in the direction of the applied field. When the field is small, the symmetric part remains identical to the distribution of the carriers in the absence of the field i.e. to the Maxwellian distribution function appropriate for the lattice temperature, and the perturbation part is proportional to the applied field. The carriers while remaining at the lattice temperature are only given a drift velocity by the applied field. Since this drift velocity of the carriers in the direction of the field is due to the perturbation component proportional to the field, the current produced by the drift motion is also proportional to the applied field and one gets Ohm's law.

When the applied field is large, the gain in energy of the carriers is so high that the whole of it cannot be transferred to the lattice through collision.
collisions until an equilibrium condition is set up in which the effective temperature of the carriers is greater than that of the lattice. Under this condition, the distribution function of the carriers may again be represented by a symmetric part and a perturbation part. But in this case the symmetric part is different from that in absence of the field and also the perturbation term is not proportional to the applied field. As a result, the drift velocity of the carriers changes non-linearly with the applied field and the current voltage relation deviates from Ohm's law. This high field non-ohmic conduction is termed "Hot-carrier Conduction", because the average energy of the carriers corresponds to a temperature higher than the lattice temperature.

Hot-carrier conduction takes place when the drift velocity due to the applied electric field becomes comparable to the random velocity. In the case of metals the thermal energy of the electrons is several electron-volts and the mobility is of the order of 20-50 cm$^2$/volt-sec, so that an electric field of the order of $10^6$-$10^8$ V/cm is necessary for creating hot-electron conduction condition. The application of such a high field across a metal sample is not feasible because of the difficulty of retaining the lattice temperature constant in the presence of large carrier concentration. On the other hand in the case of semiconductors the average energy of the carriers is of the order of one electron-volt and the mobility is a few thousand cm$^2$/volt-sec. The field required for hot-electron condition in this case is, therefore, of the order of a few kilovolt per cm and with the low carrier concentration in semiconductors, the application of such a field becomes experimentally feasible.

The phenomena of non-ohmic conduction in semiconductors like n-type germanium with constant carrier density was first experimentally observed by
Ryder and Shockley in 1951. Special care was taken in their experiments to ensure constant lattice temperature and to keep the carrier density constant. Observation of hot-carrier conduction excited tremendous interest amongst research workers and extensive investigations on the theoretical and experimental aspects of the phenomenon followed.

The progress of the hot-carrier studies has been reviewed by several authors\textsuperscript{2-6} and more recently by Nag\textsuperscript{7}. In the following sections a short account of the dc high field studies on transport characteristics of n-type germanium is presented as this is the material mainly studied by the author.

1.2. Experimental studies:

Experimental data on the hot-carrier conduction characteristics of n-type germanium have been collected by several authors\textsuperscript{8-16}. The results obtained so far may be summarised as follows:

(a) At low fields the current-voltage characteristics is linear but when the field is increased beyond a critical value, the slope of the current-voltage characteristics gradually decreases and finally the current is independent of the field. However, the transition from the linear part to the saturation part occurs rather smoothly instead of passing through a distinct \( F^3 \) region (where current varies as the square-root of the electric field), as was concluded from earlier experiments. There is also a small region near the ohmic part where the current exhibits a quadratic dependence on the field. This is termed the "warm electron" region. No distinct critical field is found beyond which the decrease in the conductivity or the hot carrier region may be said to start.

(b) The conductivity characteristics has been found to be independent of carrier concentration by Prior\textsuperscript{8} and Zucker\textsuperscript{10} whereas Gunn\textsuperscript{17} detected a variation.
of the characteristics with the carrier concentration. The results are rather conflicting.

(c) Analysis of the data for different lattice temperatures like 298°K and 77°K shows that though the general features of the current voltage characteristics are the same at different temperatures, distinct anisotropy effect in the values of mobility is observed at 77°K. The longitudinal anisotropy, has also been found to be pressure dependent by Koenig et al. 11.

An electric field transverse to the direction of the applied field is also found to appear 14, 16, 19. The magnitude of this field increases with the applied field and finally attains a saturation value.

1.3. Theoretical Studies:

The theory of hot carrier conduction involve the solution of Boltzmann equation. For a many valley semiconductor the equation, in the dynamical equilibrium conditions, of the motion of the carriers in the presence of a time independent field, can be written as

\[ \frac{\partial f}{\partial t} \bigg|_{\text{field}} + \frac{\partial f}{\partial t} \bigg|_{\text{collisons}} = 0 \]  

... (i)

where \( f \) stands for the distribution function in a particular valley and the collision term is due to scattering by the acoustic phonons, optical phonons, inter-valley phonons, impurity centres and other carriers. In order to solve Eq. (1), the distribution function has been expanded in terms of spherical harmonics, of which only the first two terms have been generally retained, because the terms higher than the second one can be shown to have negligible contribution to the current even in presence of the highest applied field. One thus writes

\[ f = f_0 + \bar{k} \cdot f^* \]  

... (2)
where $\mathbf{k}$ is the wave vector, $f_0$ is the symmetric term and $f_1$ is the perturbation term. The exact forms of $f_0$ and $f_1$ are required to be obtained by putting (2) in (1) and solving the resulting equations. Different methods have been adopted for obtaining the solution.

In one method\textsuperscript{20-25} the inter-carrier collisions have been completely neglected and the distribution functions, $f_0$ and $f_1$, has been obtained by complete solution of Boltzmann equation. In this method the analytical expressions used for the relaxation time, $\tau$, are identical to that at low fields, but certain simplifying assumptions are introduced to make an analytical solution of (1) possible. Yamashita and his co-workers\textsuperscript{20-22} in their series of papers developed the theory based on this method. The theoretical development by Reik and Risken\textsuperscript{23-25} is essentially the same as that of Yamashita et al., but the deformation potential formalism has been adopted.

In the second method\textsuperscript{26-28}, it has been assumed that the inter-carrier collisions are strong enough to cause sharing of energy between electrons and to establish a Maxwellian distribution at a higher effective carrier temperature. The unknown carrier temperature is obtained by using the relations between the mobility and the carrier temperature for the different scattering mechanisms and the energy conservation law. This method was followed by Shockley\textsuperscript{26}, Conwell\textsuperscript{27} and Conwell and Brown\textsuperscript{28}. They assumed isotopic effective mass and considered only the acoustic and optical phonon scattering.

A variation of the second method has been developed by Dykman and Tomchuk\textsuperscript{29-32} in a series of papers where the symmetric part of the distribution function has been taken to be Maxwellian. Using the momentum balance condition and considering the effects of electron-electron scattering, acoustic and optical
phonon scattering and impurity scattering, an expression for the current involving the carrier temperature has been obtained. The unknown electron temperature is determined by using the energy balance equation, the loss of energy by electrons being assumed to be only due to lattice scattering.

In the third method\textsuperscript{12,33-35}, the inter-carrier collision is assumed to cause energy sharing as well as momentum sharing between the carriers so that the distribution function is Maxwellian at a higher effective carrier temperature and the momentum of all the carriers is displaced by the same amount. The carrier temperature and the displacement in momentum are obtained by using the energy conservation and the momentum conservation conditions. This method was first outlined by Frölich and Paranjape\textsuperscript{35} and Stratton\textsuperscript{34}. Sato\textsuperscript{35} and Barrie and Burgess\textsuperscript{12} used this method to obtain numerical values of the conductivity. Sato assumed an isotropic effective mass while Barrie and Burgess took into account the many valley band structure. It has been shown by Stratton\textsuperscript{34} that these three methods should be applicable for three different ranges of carrier concentrations. First method would be applicable for low concentration, second method for intermediate concentration and the third method for high concentration.

1.4. A Comparison between the Theories and Experiments:

On analysing the numerical results\textsuperscript{7} obtained from the different theories one may make the following conclusions:

(a) Though theoretically three methods should be applicable for three ranges of carrier concentration, all of the three methods are equally successful in explaining the conductivity data for n-type germanium at 298°K except at very high fields, when saturation occurs. It is, hence indicated that the effect
of inter-carrier collision is not of much significance for the conductivity characteristics and the conductivity mobility would be independent of carrier concentration in n-type germanium.

(b) It has been established that the optical phonons play a dominant role in explaining the gradual change in the conductivity characteristics and the attainment of saturation at high fields. However, the optical phonon deformation potential constant as estimated from the saturation drift velocity has been found to be somewhat lower than the value obtained by other methods. This discrepancy indicates that in the saturation region the scattering mechanism is drastically altered.

(c) The results on anisotropy characteristics of n-type germanium (except when saturation occurs) is also correctly explainable, if the change in the population of the carriers in the different valleys due to the intervalley phonon scattering is properly taken into account. The characteristics at 77°C do not, however, exhibit as good an agreement. The dependence of anisotropy characteristics on carrier concentration, however, requires further theoretical and experimental studies for clarification.

(d) The hot carrier characteristics are quite sensitive to the relative strength of scattering by the acoustic, optical and inter-valley phonons. A detailed study of the characteristics would help in the assessment of the relative importance of these scattering mechanisms.

1.5. Hot-carrier Galvanomagnetic Characteristics:

In view of the fact that at low fields the study of galvanomagnetic properties of semiconductors provide informations which are extremely helpful
in understanding the scattering mechanism, it would appear that this aspect of the high field conduction in semiconductors merits a thorough investigation for clarification of the scattering characteristics.

Although extensive work has been done on dc high field conductivity characteristics, the high field galvanomagnetic properties seem to have received comparatively less attention. Only some theoretical studies have been made in this field but very little experimental data have been collected.

On the theoretical side investigation was first done by Sodha and Eastman, who deduced an expression for the Hall mobility assuming spherical Fermi-surface and considering only the acoustic phonon scattering. The results calculated from this expression do not agree even qualitatively with the experimental results obtained by Yamamoto et al. Conwell has also studied the problem and derived an expression for the Hall coefficient in terms of a conductivity matrix. Evaluation of the elements of matrix requires the knowledge of the distribution function of the carriers and the energy dependance of the momentum relaxation time. A treatment of the non-ohmic and anisotropic effects of galvanomagnetic coefficients for warm electrons in many valley semiconductors considering the scattering by acoustic and optical phonons has been presented by Tsutsumi. It has been shown that all of the galvanomagnetic coefficients for warm electrons in n-type germanium can be obtained in the form of the quadratic dependance on the electric field strength for the whole region of magnetic fields. Matz and Garcia-Moliner and Budd have recently studied the problem of the galvanomagnetic transport properties in an intense electric field in some details. The former authors have studied the non-ohmic transport phenomena in a magnetic field with the emphasis on galvanomagnetic effects in the absence of the Hall field. Budd in his first paper calculated the
Hall coefficient for high electric fields in a many valley semiconductor and showed that it is independent of the electric field. The distribution function for the hot-electrons in high magnetic fields were also calculated at high and at low temperatures for acoustic phonon scattering only. In his second paper, the electron distribution function has been calculated for a many valley semiconductors for the case of anisotropic scattering by acoustic phonons at low temperatures. In the third paper an analytical study of the hot-electron magneto-conductivity assuming isotropic effective mass with acoustic phonon scattering and impurity scattering has been made. The effect of inter-valley scattering has also been outlined for silicon with electric field in the $(100)$ direction and magnetic field in the $(111)$ direction. In view of the assumptions made, these results are likely to be applicable for $n$-type germanium only at low temperatures.

A realistic assessment of the galvanomagnetic properties of the hot-electrons in many valley semiconductors like germanium would necessitate an accurate treatment considering the contributions of all the scattering processes. Using the low carrier concentration model, Nag and Das first obtained the distribution function of carriers in a many valley semiconductors assuming acoustic phonon, optical phonon and inter-valley scattering. The expression for the Hall mobility has also been derived and some numerical computations presented. It has been found that the Hall mobility is anisotropic and exhibits maximum and minimum values when the electric field is applied respectively in $(100)$ and $(111)$ directions. Generalised expressions for the magnetoresistance coefficients for any arbitrary direction of the applied electric field and magnetic fields have been given by Das. The expressions are, however too complicated for the discussions of the distinctive features of the characteristics.
Recently Nag and Guha\textsuperscript{46} have studied the galvanomagnetic phenomena in n-type germanium for the case when the carrier concentration is large enough to ensure a Maxwellian energy distribution, displaced in the momentum space, in each valley. Numerical values for the Hall mobility as obtained by them agrees quite closely with that obtained from the low carrier concentration model. From the values of the magnetoresistance as calculated by them, it has been suggested that the magneto-conductivity in n-type germanium would be dependent on the carrier concentration, the verification of which necessitates a detailed study of magnetoresistance in low and intermediate concentration ranges.

1.6. Conclusion:

Considering the hot carrier galvanomagnetic studies in n-type germanium as discussed in the preceding section one may arrive at the following conclusions.

(a) Though it has been felt that the study of high field galvanomagnetic phenomena would be of immense help for the clarification of the scattering characteristics, only relatively little work has been done. The hot-carrier Hall mobility has, however been studied theoretically to some extent, but little experimental data have been collected.

(b) Secondly, as the magnetoresistance is more sensitive to the carrier distribution function and scattering mechanisms than the mobilities, it would be useful to make a very detailed examination of the hot-carrier magneto-resistance characteristics.

There, indeed, remains a wide scope for the detailed theoretical and experimental study of the hot-carrier magnetoresistance and Hall mobility of n-type germanium. The present author has been engaged in the study of these characteristics since 1982 and the present thesis embodies the results of
these studies. The detailed scope of the thesis is given below:

1.7. Scope of the Thesis:

The contents of this thesis are presented in two parts. The first part consisting of Chapters II, III and IV deals with the theoretical study of dc hot-carrier galvanomagnetic characteristics of elemental semiconductors with particular reference to n-type germanium at 300°K. To be specific, in Chapter II, a general theory of hot-carrier galvanomagnetic characteristics for negligible inter-carrier collision model has been developed by the author.

In Chapter III, from the general theory are obtained the expressions for Hall mobility, transverse- and longitudinal magnetoresistances and their coefficients assuming spherical-constant-energy-surface-model. Calculations of these quantities have also been made for different electric fields with the parameter values of n-type germanium at 300°K considering (a) pure acoustic phonon scattering and (b) predominant optical phonon scattering.

In Chapter IV, the expressions for the above mentioned constants in either cases of scattering are obtained considering many-valley band structure. The characteristics obtained after calculations have been discussed in details and the relative contributions of acoustic phonon scattering, optical phonon scattering and inter-valley scattering have been assessed. The effect of anisotropy in the scattering has also been studied. The dependance of galvanomagnetic constants on the optical phonon deformation potential constant, D_o, has also been investigated and it has been shown that the measurement of the galvanomagnetic constants may throw some light on the value of D_o, which is yet not very accurately known.
In the second part of the thesis the experimental work done by the author are described. The experimental arrangement set up by the author for dc hot-carrier measurements on semiconductors has been described in Chapter V.

In Chapter VI, the hot-carrier experiments on n-type germanium at 300°K have been described and the data collected therefrom for Hall mobility, transverse- and longitudinal magnetoresistances has been presented. In the concluding sections of this Chapter (Sec. 6.6 and 6.7), a comparison between the theory and the experiments has been made.

The author has also performed some hot-carrier experiments on the samples of near intrinsic germanium and on the surface conductance of n-type germanium. These have been described in the last chapter i.e. Chapter VII.