1.1.1 **Hot Carrier Effects in Semiconductor**

The charge carriers in a semiconductor gain energy from an applied electric field and at the same time relax it to the surrounding lattice atoms. As the electric field strength is increased the energy relaxation process becomes nonlinear. At high fields the carrier is said to have its self energy \( \langle \varepsilon \rangle \) different from equilibrium value \( \varepsilon_0 \) and is termed as hot carrier. A hot electron in the semiconductor is an electron with energy more than a few KT above the fermi energy, where \( K \) and \( T \) are Boltzman's constant and lattice temperature respectively. The study of hot electrons in solids was first initiated by Landau and his collaborators in mid nineteen-thirties. Landau's work was mainly concerned with dielectric breakdown and was mostly theoretical. The first experimental work on high field transport phenomena in homogeneous semiconductors like Ge and Si was reported by Shockley [1]. Later on, Stratton [2] presented a theory on hot carrier effects in compound semiconductors. Since then hot electron physics has become a lively field of research in its own right, going significantly beyond specific device modifications.

Primarily, the investigation of high field transport gives the information on the details of electron-phonon
interaction, the interaction of a carrier with other impurities and the interaction of carrier with other carriers \[3,4\].

Later on some new phenomena due to high electric fields have been found, e.g., the anisotropy of the conductivity in cubic crystal \[5\], current instabilities due to negative differential mobility at high fields caused by the population of higher lying conduction band minima \[6\], generation of acoustic flux which is related to a strong disturbance of the phonon distribution \[7\], avalanche effects \[8\], electron emission from cold cathodes \[9\] etc. A remarkable change in conductivity has been observed at low temperature in Si, Ge and GaAs due to impact ionisation of shallow level impurities by the hot carriers. At room temperature the change in carrier concentration occurs in the bulk of semiconductors placed in a high electric field because the capture rate of a carrier by a trap depends on the velocity of the carrier which increases with field strength. The important applications of high field induced phenomena are: free carrier contribution to the dielectric constant, inducing infrared absorption due to free carriers, Hall effect, magneto resistance effect and the recombination effect of hot carriers.

A hot electron is characterized by an 'electron temperature' which is a measure of its average energy. The average energy acquired by an electron can be estimated from all the scattering phenomena in the lattice. In general there are two types of scattering in terms of energy lost or gained by the carrier from the field, i.e., elastic and inelastic scattering.
In case of elastic scattering the energy gained by the carrier from the field will cause mainly an increase of the mean thermal energy. The drift velocity will remain low in comparison to the thermal velocity. If however the collision occurs at large angles, which results in loss of carrier energy then it is called inelastic scattering.

The application of the magnetic field (B) superimposed on a strong electric field will cause a reduction in the rate of gain in energy due to the deflection of the carriers caused by the Lorentz force. Thus a magnetic field will give rise to a cooling effect, i.e., the mean carrier energy at a certain electric field is reduced with the application of magnetic field [10,11]. Or it can be said that in presence of a magnetic field higher electric field is required to get the same electron temperature. Among the various instabilities, the one which is studied [12] in detail manifests itself in current or voltage oscillations with frequency ranging from a few kHz to 20 GHz in the presence of a longitudinal magnetic field of a few hundred to a few thousand gauss depending on the material. Microwave emission from InSb biased to breakdown region has been found to occur in the presence of magnetic field. It is also observed that microwave emission occurs at far below the breakdown field if the magnetic field is parallel to the sample length.

Under high field conditions there may exist a region in the J-E characteristics with $\frac{dj}{dE}$ as negative, where j is the current density produced by the field E. There are two cases
for this behaviour namely, either \( j \) being directed opposite to \( E \) or \( j \) directed parallel to \( E \) but decreases as \( E \) increases. In the former case it is due to negative resistance whereas in the latter case it is due to negative differential resistance. It was pointed out by Kogan et al \( [12] \) that a material in which energy relaxation takes place through piezoelectric scattering while the momentum relaxation is through impurity scattering, shows negative differential resistivity (n.d.r.). An example of this class of material is GaAs. The ordinary thermoelectric or Seebeck effect also occurs due to spatial distribution of carrier with temperature gradient on the sample. The spatial variation of distribution due to gradient in electric field intensity will also give rise to an open circuit voltage. The generated voltage is called thermoelectric voltage of the hot carriers.

For a semiconductor under high field application, the band structure can be visualized in more detail than under the low field case. It is due to the fact that for cubic symmetry which characterizes a majority of materials, the low field conductivity is scalar whatever the peculiarities of band structure, whereas there is no such restriction in the high field case. Since the details of band structure are quite individual to a material, characteristics behaviour of different materials will be different in high field. The carriers occupy regions near minimum band edges. The energy of the carrier may then be expanded in a Taylor series in even powers of wave vectors \( \mathbf{K} \). For energy close enough to band edges the series
may be terminated at quadratic terms and the band shape will be parabolic. The surfaces connecting \( \mathbf{K} \) (\( \mathbf{K} \) being momentum vector) values, belonging to same energy may be spheres as in GaAs and InSb. In case of silicon the band edge is not at \( \mathbf{K} = 0 \) but is at a number of equivalent points in the Brillouine Zone. The minimum for silicon is along \( <100> \) direction which results in six equivalent valleys. As the energy is expressed by a Taylor series expansion of wave vector from valley minimum, then the surfaces of constant energy in silicon band structure will be ellipsoid. For a high electric field the direction of current may be different due to anisotropy in band structure. High field transport phenomena in silicon and its comparison with other crystals have been studied in detail.[13]

Many other effects are also associated with hot electron transport phenomena such as electrical noise, Faraday rotation, thermionic emission and electron spin resonance. Faraday rotation is the rotation of plane of polarization of a plane polarized electromagnetic wave passing through the sample with a static magnetic field along the direction of free carrier wave propagation. It has been also observed that [12] heating of carrier in semiconductor results in emission of electron from surfaces. The experiment which studies the thermionic emission phenomena generally uses coating of suitable material to decrease the work function of the sample. Having seen the hot electron effects in semiconductor materials, we now proceed to study some of these effects in the p-n junctions and MOS devices.
1.1.2 p-n Junction

In the case of a p-n junction, hot electron emission is obtained when the electron energy in the junction region exceeds the electron affinity of the semiconductor. This highly energetic electron can be created by two means. (i) By exposing the bulk region of the junction to light of $\hbar \omega > E_g$, thereby producing electron-hole pairs. An electron should surmount the barrier for emission, (ii) On the other hand when a p-n junction is reverse biased by a high field, an electron from the junction can get sufficient energy to be emitted from the device. In this case emission surface is parallel to p-n junction. Emission intensity depends on several factors such as optical phonon scattering, scattering ionisation coefficient direction etc. in the semiconductor. The emission current density may reach quite high value of the order of $100 \, \text{A/cm}^2$ in some cases. A decrease in emission intensity has been obtained due to increase of surface states on the surface $[15]$. A density of surface states $8 \times 10^{12}/\text{cm}^2$ has been obtained due to hot electron emission into the oxide layer of the surface.

Recently a new phenomenon has been observed $[16]$ in a p-n junction. When light of energy less than the band gap of semiconductor falls on a p-n junction device, current of opposite polarity to that of a photovoltaic cell flows through the junction. This is termed as an optically excited hot-carrier-voltaic effect. The physics of this phenomenon is quite different from photo carrier generation in bulk of a semiconductor.
It can be attributed to inhomogeneity of carrier distribution in a p-n junction.

The hot carrier effects due to avalanche mechanism in a p-n junction produces a change in carrier concentration whereas in a homogeneous semiconductor a change in the distribution function takes place in the presence of high field. The generation and recombination of hot carriers in an avalanching depletion region cause photon emission in both visible and IR range.

Hot electron relaxation effects also determine the critical static device properties of transferred electron devices and field effect transistors. It has been pointed out by Rees in 1969 [17] that the speed limits of short transferred electron devices follow the same principle as in electron tubes, i.e., inertial electron flight effects. The higher the desired device speed the higher the field strength required to achieve it before other effects such as internal Zener effect set in.

1.1.3 MOS Devices

In MOS transistor hot carriers are generated by two mutually perpendicular components of electric field, i.e., both transverse and longitudinal components. Hence carrier transport phenomenon is 2-dimensional in general. Attempts have been made to study the high field transport phenomena as well as electron temperature determination in an inversion layer of MOS-FT [18]. The band structure of inversion layer at
Si-SiO₂ interface has been studied by infrared absorption \[19\] and emission \[20\] due to intersubband transitions. The results of the infrared studies of an inversion layer not only give the subband energy but also give an estimate of the energy received from source-drain electric field. Hence one can obtain information about the energy distribution of charge carriers. Among other high field effects, a negative differential resistance is observed in the inversion layer, due to repopulation of electrons in the six equivalent conduction band valleys of silicon. A pronounced hysteresis effect \[21\] is also observed in negative differential resistance of the inversion layer of MOS devices. This phenomenon is correlated to the number of oxide charges and most likely with trapping of electron in surface states. A detailed review of various hot electron effects in small dimension MOS devices is given in the following section as this is an area of intensive research.

1.2.1 Hot Electron Effects in VISI Devices

With the advancement of technology and inherent desire to fabricate low cost and high density integrated circuits on silicon chips, it has been assumed that \[22\] it will be possible to fabricate one million components per chip by 1990. As the device dimensions decrease both transversely and laterally the associated field strengths become proportionately high. Hence there exists very high electric field even at low biasing voltage. The study of hot electron physics in very large scale integration (VLSI) circuits is becoming increasingly important. One of the difficult physical phenomena in silicon
MOS transistor that is gaining attention in recent years is the emission of hot electrons and holes from Si-substrate to adjacent SiO₂ layer. Besides being an interesting physical phenomenon in itself, the emission of hot carrier from Si into SiO₂ has found its application in electrically programmable memory devices [23]. Also the subsequent trapping of the emitted carriers in the SiO₂ layer can result in device degradation and instability such as breakdown walkout, current gain degradation and threshold shift [24].

In a MOSFET, electrons which are accelerated by an electric field near the drain junction can acquire the threshold energy for impact ionisation and generate electron hole pairs. In n-channel devices holes flow into the substrate and cause substrate current [25]. A major part of electrons flows back into the drain region but a few of them attain energy sufficient to surmount the Si-SiO₂ barrier and are emitted into the gate oxide. Some of the emitted electrons passed through the gate oxide are collected in the gate electrode thus causing gate current. Hence the study of high field transport phenomena in IGFET deals mainly with quantitative measurement of gate and substrate current. The passage of hot carriers through insulator causes some degree of trapping and thus introduces instabilities in the electrical characteristics of the devices. The effects become more and more pronounced as these devices are scaled down in dimensions, especially when the local field becomes too high. Hot electron trapping in SiO₂ results in a net accumulation of negative charge. The negative
of oxide charge is equivalent to a lowering of gate voltage or more positive threshold voltage which increases the channel current in p-channel devices and decreases that in n-channel devices. Most of the hot carrier studies are concerned with n-channel devices rather than p-channel devices.

Since the Si-SiO₂ interface barrier energies are about 3.1 eV for electrons and 3.8 eV for holes, the hot carrier must gain these large energies to be emitted into SiO₂ from silicon substrate. Emission of hot carriers from Si into SiO₂ can be accomplished either by avalanche injection [26] or nonavalanche injection [27].

1.2.2 Avalanche Injection

Various structures are now discussed separately.

a) Gated p-n injection: Gated p-n injection can be easily biased to induce avalanche multiplication. Depending on gate bias either majority carriers or minority carriers can be injected into SiO₂ from surface accumulation or inversion at the interface. In case of deep depletion or inversion in Si surface, the absence of field crowding implies a higher reverse bias for avalanche multiplication making it more difficult to generate sufficient hot carriers for emission studies.

b) MOS capacitor studies: It is well known that a metal oxide silicon (MOS) capacitor can be driven into a 'non-equilibrium' 'deep depletion' state momentarily by applying a voltage step or voltage pulse that tends to invert the silicon surface. If
the electric field in silicon depletion region is high enough, avalanche multiplication may occur and the electrons thus generated drift towards the Si-SiO₂ interface in a p Si-SiO₂ metal structure. Most of these electrons contribute to form the surface inversion layer while a small fraction may get sufficient energy from the high field in the depletion region to be emitted into the SiO₂ layer. Thus surface avalanche in a p-substrate MOS capacitor provides a means of injecting hot electrons into SiO₂.

c) MOS transistor: Besides the above two structures, avalanche injection phenomenon also occurs in the case of a MOSFET. Carrier generation occurs from avalanche process due to high reverse bias in the drain. Depending on the relative field between gate and substrate and gate-drain boundaries either electrons or holes are emitted into SiO₂. This is the main topic of our present study.

1.2.3 Non-avalanche Injection

Non-avalanche injection does not imply the absence of avalanche multiplication during injection. It simply means that the sources of hot carriers are supplied independently rather than derived from an avalanche plasma.

1) Channel hot electrons in MOSFET: When a MOSFET is biased, the free carriers in the surface channel flow from source to the drain and gain kinetic energy from the high field region near the drain junction. At sufficiently large drain voltages the carrier may gain sufficient energy for it to be emitted into the SiO₂ layer near the drain junction.
Substrate hot electrons: The sources of substrate hot electrons are thermally generated leakage current and multiplication current initiated by leakage current. Leakage electrons are thermally generated within the depletion layer or diffused into the depletion region from the bulk neutral region. As these electrons drift towards the Si-SiO₂ interface, they gain energy from the high field in the depletion region. Those electrons which arrive at the interface with sufficient energy to surmount the Schottky-lowered interface barrier, may be emitted into the SiO₂ layer. Since these electrons originate from the substrate, the resulting effect is termed as substrate hot electron effect. In case of MOSFET substrate hot electron emission occurs when both the source and drain are grounded and only the gate is heavily biased.

Carriers supplied by underlying p-n junctions: Many of the drawbacks in avalanche injection and in the emission of thermally generated carriers are overcome by using IGFET or gated diode structures with an underlying supply junction. The electrons are injected into the p-type substrate from the underlying n⁺p junction. This supply current is controlled by the forward bias voltage applied to substrate. If the thickness of the p-type substrate is less than or comparable to the minority carrier diffusion length then some of these supplied electrons will diffuse into the depletion region and then drift towards the Si-SiO₂ interface, gaining energy on their way from the high field in the depletion region. Those electrons arriving at the interface with sufficient energy to surmount
The advantages of studying hot electron emission by this structure are many. The emission current can be controlled by varying the forward bias to the supply junction. Furthermore, as long as the silicon surface is kept inverted, both the oxide field and the field in silicon depletion region can be varied independently, the former by varying the gate voltage and the latter by varying the substrate bias.

iv) **Optically induced hot carrier injection**: The process of minority carrier injection into SiO₂ has been observed under incident light on a polysilicon gate IGFET. Polysilicon gate electrode allows the light having energy more than the Si band gap through it and thus electron-hole pairs are produced in the substrate. The hot carrier supply is proportional to the photon flux and hence can be varied by changing the intensity of light.

In VISI chips, due to generation and recombination of hot carriers, photons are produced. Photon generation process exists in both forward as well as reverse bias junctions. Photons generated by this mechanism can generate minority carriers in the substrate and discharge the sensitive nodes \[28\]. It has been reported that degradation of refresh time of DRAM and upset of SRAM are possible effects in various memory chips. To minimise the hot electron effects in short channel devices, two types of structures have been reported \[29\] by (i) Using a...
graded drain junction for reducing the electric field and
(ii) Using an offset gate for separating the gate electrode
from the localized peak of the electric field.

1.3 Brief Outline of Present Work

The above two sections briefly review the present status
of hot electron physics in bipolar and MOS devices. These
studies are mainly concerned with various instabilities and
characteristic degradation of device performance. Recently
hot electron emission phenomenon has become a research tool
for the use of data storing and erasing in Si memory chips.
However the physical processes are not well understood.
Therefore the present study has been undertaken.

In this dissertation we have reported the study of both
the visible and infrared photon emission from MOS devices in
various modes of device operations. Light emission from silicon
junctions has long been observed in both forward- and reverse-
bias p-n junction. For forward-biased p-n junction, the
mechanism of photon generation is radiative recombination and
the light emission has been used as a monitor of uniformity of
current in p-n-p-n thyristors. The spectrum of the forward-
based case has peak at 1.1 eV and a sharp cut-off at both
high and low energies. In Si MOSFET it has been reported
recently [28] that photons produced in forward biased
junction get absorbed in the Si substrate. This absorption
results in electron-hole pair generation which causes an
increase of current flow in addition to normal component.
In a reverse-biased Si junction the mechanism for photon generation is the interband and intraband transition of carriers and hot electron-hole recombination. The spectral response of both the forward-and reverse-biased silicon p-n junction is shown in Fig. 1. For reverse-biased junction, the emission cut-off wavelength (630 nm) is reached when holes reach their ionisation energy,

$$\hbar \omega_{\text{low}} = E_{\text{oh}} (1 - \frac{m_{1h}^*}{m_{2h}^*})$$

where $E_{\text{oh}}$ is the threshold energy for pair production by holes and $m_{1h}^*$, $m_{2h}^*$ are effective mass of light and heavy holes respectively. $E_{\text{oh}} = 2.9$ eV and $m_{1h}^*/m_{2h}^* = 0.32$. The high frequency limit is given by interband transition between conduction band and valence band which gives

$$\hbar \omega_{\text{high}} = E_{\text{oe}} \left[ 1 + \frac{K_c^2}{(K_c - K_o)^2} \frac{m_{c}^*}{m_{2h}^*} \right] + E_G$$

where $K_o$ is the wave vector for conduction band minimum (2/3 K for silicon), $E_{\text{oe}}$ is the ionisation threshold (1.6 eV) for electrons, $m_c^*$ is the effective mass of conduction electron ($m_c^*/m_{2h}^* = 1.94$), $K_c$ is the wave vector of radiating electrons and $E_G$ is the band gap. For $K_c = 0.26$ K in <100> direction we obtain cut-off. $\lambda_{\text{low}} = 360$ nm. This is the high frequency end of emission spectrum.

Photon emission can shift the band to band spectrum to lower energies by multiples of the phonon energy. The phonon shifted lower energy emission may be more readily
transmitted by the semiconductor due to its reduced absorption at lower than band gap energies. Hence the spectrum of light emission extends to IR range which is due to phonon assisted emission.

The total contents of the present reports are divided into various chapters and each chapter contains the subjects as follows. In Chapter II, we present the experimental procedure to fabricate the MOSFET. Various semiconductor device processing techniques are first standardised and the required data are collected. Using the available data, masks are designed by Computer Aided Design (CAD) system. Then the device is fabricated by standard n-channel metal gate experimental procedure. All the experimental parameters obtained agree with designed values.

Hot electron effects in n-channel MOSFET is reported in Chapter III. Both the theoretical model and experimental results are presented. Our work is mainly concerned with the visible light emission from Si MOSFET and its variation with different modes of device operation. A comparative study is made with gate and substrate current whose origin is believed to be the same, i.e., avalanche carrier generation phenomenon in drain-substrate depletion region. We report the visible light emission from MOSFET and its variation with gate bias for the first time. It is seen that to understand the high field transport phenomenon in detail, a study of the light emission is an useful tool.
Chapter IV contains the study of hot carrier effects in depletion mode MOSFET's. Depletion mode or normally on n-channel transistors are fabricated by phosphorous implantation through the gate. Implantation of phosphorus impurities changes the threshold voltage in negative direction. Similar to the enhancement mode transistor case, we also compare light emission with gate and substrate current of the device. Light emission differs in this case at various positions of the device boundaries.

Recently there has been increased interest on IR emission from 2D plasmon oscillation of Si inversion layer in MOSFET. This emission is due to excitation by hot carrier in the channel from source and drain electric fields. Inversion layer plasmon is an electromagnetic surface wave with certain type of polarisation. We report in Chapter V an analysis of the plasmon oscillation of 2-D inversion layer in MOSFET. Various factors such as effecting its coupling with gate electrode plasmon and the resulting frequency of emission are discussed in detail. This section contains a study on non-radiative type solution only. The possible structure to make a MOSFET as a tunable IR radiator is presented.

Chapter VI contains the study on radiative type solution. The term radiative type solution implies that the electromagnetic wave has oscillatory behaviour outside the medium so that energy can be transported from the device to outside. Theoretical calculations are compared with available experimental resonance...
absorption data. Life times of these modes of oscillations are also discussed.

Finally Chapter VII contains the general conclusions arrived at in the present work. Limitations of various theoretical models as well as the deviation of experimental values from theory are discussed in the general context. Suggestions for further studies which will enhance the insight into the understanding of high field effects in short channel MOS devices are also given.