The ion sheath is produced across any electrode or material body immersed into the plasma, if the body is biased negatively with respect to the plasma potential. The motion of the ions inside the sheath is governed by the electron temperature \( T_e \) i.e. if the negative bias of the electrode is such that, it is smaller than the electron temperature \( T_e \), no ion sheath forms in the plasma. On the other hand if the applied bias is more than the electron temperature \( e\phi > T_e \), there will be a sheath formed across the electrode and the motion of the ions will be governed by the applied voltage of the electrode.

Since the formation of the ion sheath is found to be a natural consequence in any plasma system, due to the high mobility of the electrons, the wall potential will adjust itself as negative with respect to the bulk plasma and the potential of the electrode placed inside the plasma becomes negative. The loss of electron from the plasma to the boundary wall will give rise to an electric field between the plasma and boundary wall and this electric field
resists the electron motion to the wall and enhances the ion loss to the electrode, as a result of which the ion sheath is formed around the electrode or any material body. Hence, one can conclude that there is a chance for the formation of sheath even around an unbiased electrode placed in any plasma chamber. The various properties of these sheath and the different works that have been done till now are described in Chapter I of this thesis. It also describes its application oriented fields, which are of growing interest among the plasma physicists around the world.

This thesis presents the experimental results obtained during investigation of an ion sheath produced across a negatively biased grid in a collision free low density beam plasma system in different chapters. However, the present chapter concludes the major findings elaborated in the preceding chapters. Section 7.1 describes the major success of this investigation and also the various results obtained. Section 7.2 attempts to suggest scope of future studies that are still open specially on ion sheath as well as the application motivated study on ion sheath in different plasma configurations. The different possibilities in the application of the plasma sheath on material processing are also described in this section. There are also possibilities of some other types of ion sheath in plasma, which have not been completely focused yet i.e. they are neither described nor investigated properly. A few examples of such types of sheath are the sheath around the limiter and divertor in fusion devices, strongly magnetised ion sheath, the sheath around antenna, the sheath around electrode in RF discharges, sheath around the cathode in high pressure arc devices, faraday shield around the electron cyclotron resonance heating devices etc.
7.1 Summery of the Major Results Obtained

This study is concerned with the sheath induced nonlinear phenomena in laboratory plasma and especially in a double plasma device and in a ECR plasma system. The experiments are carried out in a double plasma device, where the ion sheath is produced across a negatively biased grid, which separates the devices into the source and the target section respectively (described more elaborately in Chapter II). The ion sheath is formed around the grid by biasing the grid negatively with respect to the ground. This sheath is considered as collision free because the mean free path of the system is generally more than the scale length of the device. In the ECR plasma system, two types of mesh grid of different hole sizes are used for sheath formation where the grids are biased negatively (described in Chapter VI). Four different diagnostics (Langmuir probe, Emissive probe, Energy Analyser and Faraday Cup) are used to measure the different plasma parameters in the system. The Langmuir probe is generally used for plasma density and electron temperature measurement, the ion energy analyser is used to measure the ion temperature as well as ion energy distribution of the plasma, the emissive probe is used to measure the plasma space potential axially both in the source and the target chamber and the faraday cup is used to measure the ion current density in the ECR system. From the potential profile curves by emissive probe the sheath thickness is calculated (sharp fall of plasma potential in the potential profile curve) and the sheath structure is found to follow the well known Child Langmuir law for the space charge limited current, when the density of both source and the target chamber is almost same (Chapter III). Under the same density ratio condition an ion beam is injected into the source section of the chamber in order to make the plasma unstable. The presence of the ion beam is detected with the help of an ion energy analyser in the target section of this
chamber. In this experimental condition, there exist both the beam mode and the ion acoustic
mode in the target section, which is described by experimentally measured dispersion
relation. However, the presence of beam mode and the ion acoustic modes simultaneously
exists in the plasma only in some particular cases (Chapter III). The beam enhanced
instability and the effect of beam on sheath structure are also studied in this chapter. It is
observed that the plasma becomes unstable for the applications of source anode biasing
voltages \( (V_s) \) for the beam and grid biasing voltages \( (V_g) \) under certain conditions when the
plasma density is same on both sides of the chamber. In this circumstance, the plasma
becomes unstable due to the potential difference in the source and the target chamber
produced by the application of voltage in the source anode and also due to the effect of
sheath formed by \( V_g \). The instability frequency that has been observed in this condition is
found to be resonance coupling of free fall ion beam due to the potential difference (termed
as \( v_b \)) and the ions moving with a velocity toward the grid (termed as \( u_g \)). This value of \( v_b \)
and \( u_g \) are calculated for different conditions of the system i.e. for various values of \( V_s \) and
\( V_g \). These results highlight that the excitation of the instability frequency is occurring for
various range of \( v_b/u_g \) for different value of \( V_s \) and \( V_g \). The maximum instability is observed
when the value of \( v_b \) and \( u_g \) are almost equal i.e. when \( v_b = u_g \). This condition is also called
the resonance condition for the excitation of the instability. The instability nature of plasma
is calculated for different value of \( v_b/u_g \) and it is found to be well within the particular range
of sheath thickness and when \( 0.5 \leq v_b/u_g \leq 2.0 \).

The region of the instability growth is also observed in the same experiment with the
help of interferometer technique by applying a test wave of frequency almost same with the
The region of the instability growth is also observed in the same experiment with the help of interferometer technique by applying a test wave of frequency almost same with the instability frequency. It is found that the maximum growth of instability occurs within a particular distance from the grid or sheath, which is termed as the presheath region. The experimentally observed presheath region in this experiment is found to be well in between 1.0 cm to 4.0 cm.

Experiments are also carried out in the double plasma device by taking into consideration of the different density ratio of the source to the target chamber. This is done by fixing the source plasma potential at a higher value (density $n_s$) and varying the target plasma density (density $n_T$) from lower to higher value. In this case the observation of the characteristics of the sheath induced instability has been done for four different (density ratio) value of $n_T/n_s$ viz. 0.3, 0.35, 0.5 and 0.6. The characteristics of the instability frequency and the cause for its existence are observed with the help of different diagnostics. The dependence of the instability frequency in this case are not only the density ratio, but also the sheath thickness and the source anode biasing voltage. The density ratio 0.5 is termed as a critical ratio in this experiment (Chapter IV). Below and above this critical density ratio, the instability characteristics are completely different. Observations are made for the excitation of instability with respect to grid biasing voltages ($V_g$) at a particular $V_s$ value and density ratio. It is observed that for a fixed value of $V_s$, a particular threshold value of $V_g$ is required to excite the instability. This threshold value of $V_g$ required to excite the instability is also observed from the energy analyser characteristics of the beam in the target section. When the density ratio between the source and the target section is very low i.e.
around 0.3, then there are also flow of some low energetic ion beams from the source to the target section. This low energetic ion beams cannot detected with the help of ion energy analyser, when \( V_s = 0 \) V. However, this can be detected with the help of Langmuir probe characteristics. If a biasing voltage is applied to the source section of the chamber, then the instability is excited due to the resonant coupling of the beam ions and the background ions which are detected with the help of ion energy analyser. The I-V characteristics of ion energy analyser (Chapter IV) with respect to \( V_g \) at a particular \( V_s \) shows that for a particular \( V_g \), the energy of the beam ions and the background ions are not separated and the current becomes maximum i.e. resonance takes place. It is also seen that the value of \( V_g \) for which the ion current becomes maximum is also the same threshold value for the excitation of instability in the frequency trace seen from the spectrum analyser data (Chapter IV).

Another important result that has been obtained from this experiment is that, when the density ratio is very small (i.e. \( n_r/n_s = 0.3 \)), a hump is found to be observed in the potential profile curve near the sheath edge in the target side of the chamber. This hump is the cause of chaotic phenomena in the double plasma device, which is elaborately described in the Chapter IV of this thesis.

Experiments are also done in presence of multicomponent plasma with negative ions in a double plasma device. For the production of negative ions, SF\(_6\) gas is injected into the chamber in presence of simple two component Ar plasma. The effect of sheath phenomena in presence of negative ions is studied in detail in the Chapter V of this thesis. It is found that due to the introduction of the negative ions i.e SF\(_6\) gas into the Ar plasma the sheath thickness increases and the sheath structure strictly follows the well known Child Langmuir
The low frequency instability, which is excited due to the presence of negative ions in the Ar plasma is also studied in Chapter V of this thesis. The typical nature of this instability frequency is studied and compared with the frequency excited in the simple two component plasma (Chapter III) under the same conditions. It is found that the instability is excited in this case also due to the resonant coupling of free fall ion beam as well as reflected ions through the sheath. It is seen very carefully that the instability is induced by the sheath (across the grid), when the ratio of the velocities of reflected ion beam \( v_p \) and the free fall ion beam \( v \) falls in the range \( 0.5 < \frac{v_p}{u_o} < 1.0 \), which is rather small in comparison to the simple two component plasma, where it was found in the range 0.5 to 2.0.

The effect of an externally produced ion sheath in ECR plasma source is also studied briefly (Chapter VI), where the plasma density is higher \( 10^{10} \) to \( 10^{11} \) cm \(^{-3}\) compared to the double plasma device \( 10^8 \) to \( 10^9 \) cm \(^{-3}\). The ion sheath is produced around the grid at a particular distance from the source in an ECR plasma device. It is seen that the sheath structure is drastically changing the basic plasma parameters on both sides of the grid. In this experiment it is seen that the presence of sheath decreases the plasma potential in the system. Here also a very low instability frequency is found to be excited.
7.2 Suggestions for Future Studies

The study of sheath is very important for application oriented works. But before going to the application part one has to clearly understand the basic physics related to ion sheath phenomena. So, one can study the sheath related phenomena in two different ways i.e. the basic as well as the application oriented studies. Though the basic and the application oriented studies of ion sheath have already been started, but still a large part of it is wide open in various ways. Some of these studies, which can be taken into consideration are discussed below:

7.2.1 Basic Research on Ion Sheath

Sheath criterion is a very important parameter in order to detect the ion flux into the sheath. The well known Bohm sheath criterion is found to hold good for various sheath and plasma conditions. This is generally true in a collision free and Boltzmannian electron plasma case. For simplicity, the Boltzmann distribution of electrons is an assumption, but in real cases it does not happen. So, in any experiment, there must be presence of some degree of collisionality. However, there is also presence of nonthermal electrons in most of the experimental systems. So, the modification of Bohm sheath under the said effect is one of the important feature for further study.

The studies of the ion sheath, which are presently available are mainly concerned with the case where the electron temperature \(T_e\) >> ion temperature \(T_i\). But there may be certain cases where \(T_i > T_e\) i.e. ion temperature is more than the electron temperature, which
is generally possible in the limiter region of the tokamaks. So, the study of sheath under this condition may also become an important area of study among the plasma physicists.

However, in a case of glow discharge plasma, molecular gases are used in order to produce plasma without any knowledge about the percentage of the distribution of the ions. As $e/m$ values are different for different concentrations, the sheath structure will be modified. This ions enter the sheath region with different speed depending on the values of $e/m$ ratio. In glow discharge plasma, the ionisation is generally created due to the emission of secondary electrons from the cathode and which are interacting with the plasma particle. These electrons, which are originating at the cathode and move along the electric field lines of the sheath, may or may not produce any ionisation in the sheath. These secondary electrons, which are produced in the sheath because of ionisation will change the inside scenario, as they will try to equilibrate the plasma electrons. So, irrespective to the plasma electron temperature ($T_e$), the ions in the sheath edge will generate a modified temperature region and hence there may be a modification of sheath criterion. This is also an important area of study related to ion sheath.

Interesting features related to the sheath deal with the properties of charge particles inside the sheath. The more important study on sheath is the measurement of various sheath parameters. However, it is well observed by the scientists that the study of these sheath parameters is not an easy job. The quantity which are measurable with sufficient accuracy are the electrode bias and the electrode current. The sheath created by a planer electrode no longer remains planer, and the actual sheath dimension cannot be figured out from the electrode current. Usual probe technique also fails to measure the plasma potential accurately because of the formation of extra probe sheath at the top surface of the probe. So, the probe
theories are generally based on the basis that the probe are surrounded by plasma. Hence, one can try to develop the probe theory, which can be inserted well within the sheath region. In doing so, one can consider various aspects, such as the effect of the probe area which may disturb the sheath parameters to some extent. The alignment of the probe with reference to the flow of ions within the sheath region can also be studied in detail. In the same way, there may be effect of emission that can take place from the probe surface due to the interaction of high energetic ions on the sheath. So, if one can consider these effects and understand it very carefully, then a new type of probe can be used as a very effective equipment to measure the various sheath parameters. Generally the above mentioned issues regarding the probe is very complicated to handle and this may be the cause for not developing any well defined probe diagnostics till date. Hence, the new probe diagnostics within the sheath would be an emerging as well as challenging area in the near future as far as the experimental physicists are concerned.

There is only one measurement of plasma potential available till now with the help of an electron beam technique (Goldan et al. 1970). But this experiment was done to measure the plasma potential in a sheath around a floating electrode. In this case the sheath is not so strong as the floating potential of the probe is of the order of few $T_e$. So, the use of electron beam, where a few kV of potential difference exist is not an easy job to study. Since due to the very high electric field inside the sheath, the deflection will be very high unless the beam energies are significant. The interaction of these high energetic beams with the plasma and the sheath must be a known factor. The beam density may be reduced in order to avoid some of the difficulties, but to study the effect of this low density beam, a very sensitive beam detector must be used. The electron beam, which is to be shot must be parallel to the
electrode surface in order to get an equipotential surface. But due to the increase of beam energy there may be some additional problems in the sheath region.

These are the various aspects of basic research that can be pursued on sheath related phenomena.

### 7.2.2 Application Oriented Future Study on Ion Sheath

The application oriented study of plasma sheath is now an important area. Energy, materials and information are the three bases on which the industrially advanced modern society exists. Out of which the material technology deals with the production, transformation and the conservation of materials. Industrially relevant materials already exist in the form of oxides from which it has to be extracted and purified. Alloys and compounds have to be created through metallurgical and chemical processes. But how the plasma assist in material processing is an important area of study.

Plasma technology enters the area of material processing technology as a tool to perform this function of production, transformation and conservation. The plasma surface interaction plays a very important role in large number of thin film deposition processes used for synthesis of materials - metals, alloys, compounds of almost every material are in the thin film form. The so called plasma assisted deposition processes have been extremely successful because of the possibility of obtaining materials in nonequilibrium form. There are two aspects of plasma related technology which can be discussed separately, i.e., the physical and the chemical processes. The physical aspects are caused by the energetic ions, neutrals and electrons generated by the plasma deposition process. These particles arrive at the substrate surface in a more complex manner and causes the spectacular microstructural
changes, even sputtering to some extent and also ion implantation. However, the chemical
effects of plasma results from the chemical reaction of the species generated by various
mechanism within the plasma. The film produced by either chemical or mechanical process
are not same as the bulk materials. In many cases they contain impurities, density
vaporisation, internal and external surface interfaces etc. These are the various aspects that
one can taken into consideration related to the application oriented future studies.

**Interaction of Positive ions With the Surface**

When a positive ion impinges on a surface, it can be reflected as ions or as neutral
atoms. In other way it also can remove atoms from the surface or electrons from the surface
which needs substantial study. This process of impingement of ions on the surface is
generally called the interaction of the positive ions with the surface.

Reflection: The majority of the positive ions incident on the surface are getting reflected at
all angles with certain loss of energy. The reflection of these ions from the surface occurs at
a very high energy and its necessary dependence have not been studied in detail yet.

**Neutralization**

If the atom has an unoccupied energy level $E_u$, either in the ground state or in the
excited state, whose energy equal to the occupied level energy in the metal, a resonance
transition occurs from the metallic level to the unoccupied energy level. This transition has a
high probability as it takes place between two states of equal energy in a case when the ion is
very close to the metal surface. If $E_i$ is the ionisation potential of the metal, the condition for
the positive ions to be reflected as a neutral atom is
If \( E_i \) is the energy level in the ground, excited or metastable state and the above conditions are satisfied, then the ions will be reflected as neutral. A comprehensive study of this type neutralisation due to the reflection of positive ions is an important subject of study.

**Sputtering**

The sputtering using plasmas depends on sheath properties for its effectiveness. It is an important consequence of the impact of ions on to a surface. For efficient sputtering it is necessary to choose the right energy distribution of the ions for which the sputtering has the highest cross-section, i.e., during sputtering the atoms on the surface are injected as a result of impact of ions with sufficient energy. The sputtering yields defined as the number of ejected atoms per incident ions depends on the mass, energy and the incident angle of the ions. The sputtered atoms have energies much higher than the thermally evaporated atoms. Also there is a threshold energy below which sputtering does not occur and in other way the sputtered yields decreases with the increase of ion energy because of the ion penetration below the surface. A glow discharge plasma is used to supply the ions, which are responsible for sputtering. The applied bias for sputtering is to be chosen in such a way that the incident ion current is maximum as well as it peaks around the desired energy, which is suitable for sputtering. The sputtering particles may get charged positive by the charge transfer reaction or negative by electron attachment and may again enter the sheath, which may also effect the sheath criterion and potential profile.
Secondary Electron Emission

The impact of positive ions at the surfaces can cause the ejection of electrons. These electrons can be ejected by the resonance neutralisation process. When a positive ion is neutralised near a metal surface it causes secondary electron emission, where the ions of impact must extract two electrons of which one is necessary for neutralising the ions.

Production of Negative Ions

When two electrons are emitted, it is very likely though a rare case, that the incident ion is returned as negative ions.

Ion Bombardment Induced Microstructural Changes

The various processes that occur when a growing film is bombarded with more energetic ions or neutrals depends on the variety of probe conditions. Thus, in diode sputtering, the film microstructure is strongly influenced by the gas pressure, target to substrate distance, power applied to the cathode, cathode to substrate area and overall configuration of the plasma chamber.

Ion Nitriding and Glow Discharge

A glow discharge is produced in ion nitriding by considering cathode as a target material. Though the formation of NH is assumed to be responsible for nitriding, but the position of the formation of NH is not clearly understood. One thing is very clear from this
experimental phenomena is that it is formed around or within the sheath. Hence the sheath becomes more complicated and interesting with the chemical reaction inside it. The ion nitriding relies on the thermo chemical diffusion of the ions in the target. The target also becomes hot. Hence, the effect of heat conduction across a collisional ion sheath may be one of the very important future course of study.

**Surface Plasma Interaction in Chemical Vapor Deposition Process**

The plasma enhanced vapor deposition processes have been extremely popular for microelectronic applications. The deposition of SiO$_2$, Si$_3$N$_4$, amorphous and polycrystalline silicon etc. have been achieved by applying this PECVD process. However, irrespective of the interaction of the electrons in this process, there is also possibility of ion interactions. But the interaction of ions depend upon several important steps common to most material depositions. These includes

- transport of reactive species to the growth region and the substrate surface.
- absorption of reactance and the physico-chemical reactions on the surface.
- desorption and mass transport by the products to the main gas stream and then away from the gas region.

**Plasma Etching**

Plasma etching is one more example of plasma surface interaction and are extensively used in semiconductor industry for pattern generation. The most common application of this process is the etching of silicon and silicon oxides and nitrides in a discharge CF$_4$ to form volatile SiF$_4$. This reaction generally occur at a much lower temperature and hence the
temperature controlled chemical reactions are avoided. Also a very fine resolution pattern (of the order of 1 \( \mu \text{m} \)) can be achieved as plasma etching offers a directional etching with very high selectivity.

Limited supply of etching species may result loading effect in the system. Due to the production of etched surface, the etching rate decreases. In oxide etching, the liberation of oxygen may be more than the offset consumption of etching species and each rate becomes higher. The flow of gases and removal of byproducts play a very important role in the plasma etching process. The overall flow rate depends upon the following two factors:

(a) Low flow rate of etching species and high utilisation rate may limit the etching rates.
(b) High flow rate accompanied with the increased pumping speed may remove some of the active species before reaction.

**Ion Sheath in Plasma Immersion Ion Implantation (PIII)**

It is already discussed in the introduction of this thesis that Plasma Immersion Ion Implantation (PIII) is an emerging technology for the production of improvement of surface properties of engineering technology. With the help of PIII, the surface modification of material processing cannot be treated at elevated temperature. However, the implantation of high energy ions into the surface regions of the target results in chemical and microstructural changes at the surface, which leads to improvement of the substances implanted against wear, fatigue etc.

There are various types of ion-target interactions, like sputtering, backscattering, secondary electron emission, implantation etc. Each of these reactions has a particular energy
Thus the study of this different energy distribution is very necessary. A detailed study of these energy distribution will be a fruitful future research area.

Plasma immersion ion implantation can also be done on non-metallic targets. The non-metallic target because of their low electrical conductivity, does not neutralise the ions during implantation. So, the surface of non-metallic substance remain positively charged and which prevents the acceleration of further ions into it. However, the study of temporal behavior of the sheath with reducing electric field, the reduction being dependent on the charging rate of the target, has not been performed completely yet.

Again there may be production of heat, when the ions are striking or incident on the target. Though there exists a model (Blanchard 1994), by which one can estimate the value of the temperature, but a more developed method can be formulated. For this, there may be a chance of producing suitable and necessary diagnostics technique.

The implantation of neutral ions on the target is generally attainable by producing metal ions on vacuum arc and subsequent movements of them into the target. The target is kept at a certain distance and a biased pulsed negative voltage is applied to the target. In this condition the metal ions will experience two different kinds of force (i) one is the force of expansion due to the arc properties and (ii) the force experienced due to the electric field caused by the biasing voltages on the target. Hence, the sheath properties which are generally formed around the target by the metal ions with high thermal energies is very essential to understand for plasma immersion ion implantation purposes. So, this will be a challenging future task for the scientists.

Hence, irrespective of PHI, there are also other processes which are useful for the ion sheath and are already discussed above.