Plasma Diagnostics
Introduction to Langmuir Probes

Introduction

A Langmuir Probe is a powerful plasma diagnostic tool which capable of determining the fundamental characteristics of a plasma; namely the ion number density, electron number density, electron temperature, electron energy distribution function (EEDF), floating potential and the plasma potential. Langmuir probes are routinely used to determine the plasma parameters in areas as diverse as: low pressure plasmas for materials processing, the design of ion sources & new plasma chambers and edge plasmas in fusion devices. This information is used to characterise individual systems and processes and also to design new systems. Appendix I explains in more detail the significance of each of the aforementioned parameters.

The measurement itself is accomplished by inserting a small (usually cylindrical) probe into the plasma and applying a variable voltage to the probe whilst measuring the resulting current drawn from the plasma. The current as a function of probe voltage is referred to as the I-V characteristic and it is this characteristic which is analysed to determine the various plasma parameters. The probe dimensions are chosen to cause minimum disturbance to the plasma (typically of the order of 10 mm length and 0.15 mm diameter) and provide a localised measurement of all the key parameters with very good spatial resolution.

A simplified schematic of a probe circuit and a typical I-V characteristic are shown below.

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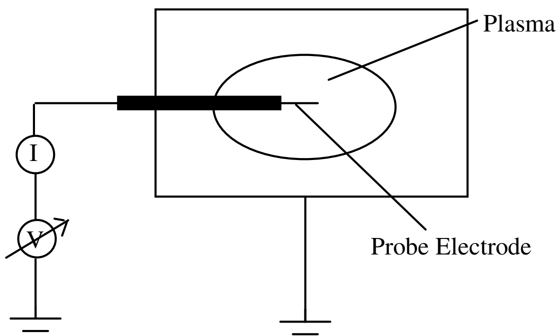
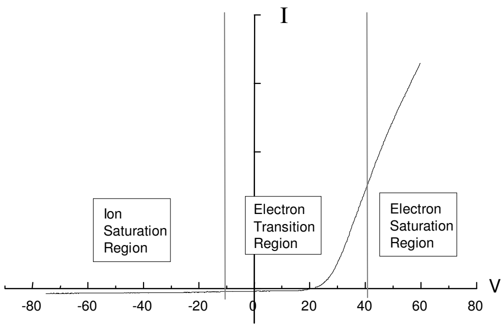


Simplified Langmuir Probe Circuit



Typical I-V Characteristic

Langmuir Probe Circuit

The simple probe system consists of an electrode, an adjustable power supply and a means to measure the current. In practice, a computer based data acquisition and control system is usually employed to automate the task of sweeping the bias voltage and recording the resulting I-V characteristic. Once acquired the I-V characteristic can then be analysed according to established theories and techniques.

I-V Characteristic

The I-V characteristic represents the current to the probe from the plasma electrons and ions as a function of probe bias. To enable analysis, the I-V characteristic is divided into three regions - the ion saturation, electron transition, and electron saturation regions. This division is useful from the point of view of understanding the shape of the I-V characteristic and more importantly in analysing the data.

- Ion Saturation Region

The ion saturation region occurs for very negative probe biases over which the negative probe potential repels all electrons and attracts only positive ions.

- Electron Saturation Region

In the electron saturation region the probe collects electrons and repels all ions.

-Transition Region

The intermediate transition region contains the electron energy information since the increasing positive probe voltage repels electrons of progressively higher energies and hence samples the distribution of electron energies. The transition region is a composite of both electron and ion current and for proper analysis ion current and electron current must be de-coupled. This is usually accomplished by fitting a function to the ion current deep in the saturation region and extrapolating it back through the transition zone. This ion current function is then subtracted from the raw I-V data to produce the electron current characteristic.

The analysis of the characteristic then

follows utilising several well known theories of interpretation.

Hiden's ESP*ION* - Advanced Langmuir Probe automates this entire process

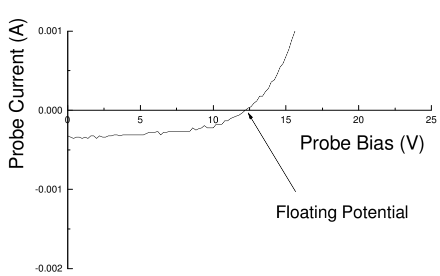
The complete process of measuring the I-V characteristic, analysing and displaying the results (as a function of time, position or other external parameter) requires little prior knowledge by the operator.

An overview of the entire automated analysis routine using the standard **ESP***ION* technique follows.

Step by Step Analysis Overview

- Floating Potential

The floating potential is the easiest parameter to determine since it is by definition the voltage at which the probe collects no current. A simple scan of the I-V characteristic will yield the floating potential:

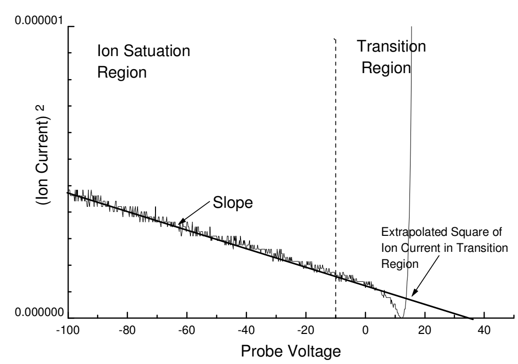


- Ion Number Density

The ion saturation zone is analysed to give the ion number density. The two main (and easily implemented) theories that can be used are the Orbital Motion Limited (OML) technique of Laframboise and the cold ion approximation of Allen, Boyd and Reynolds (ABR). Hiden's Windows™ ESPsoft software offers both interpretations. The OML technique is considered briefly here.

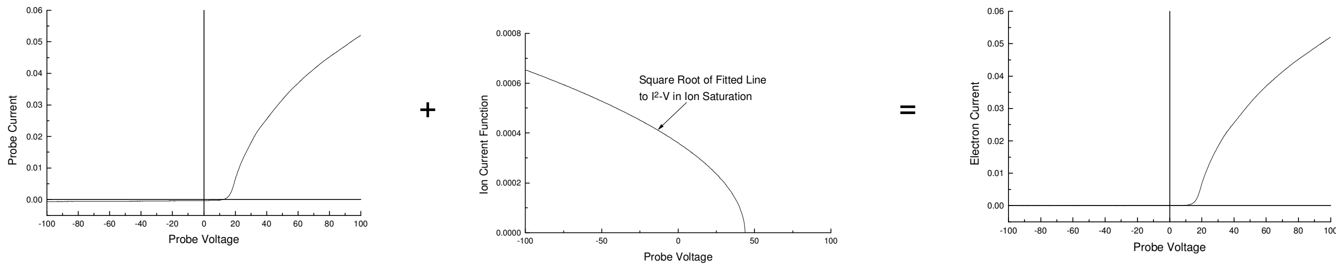
In short, a line is fitted to a plot of I^2 versus V in the ion saturation region as shown, and the slope of this line is used to calculate the ion density according to the relation:

$$n_i = \frac{1.42x10^{15} M\,(amu)^{1/2}(-slope)^{1/2}}{A_p\,(m^2)}$$



- Electron Number Density, Electron Temperature & Plasma Potential

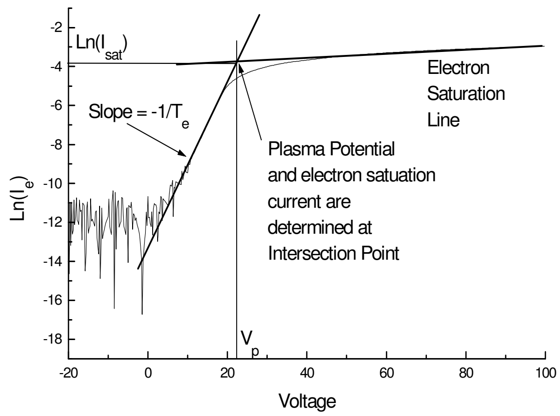
The square root of the ion current fit is added to the original I-V data to obtain a characteristic which consists of an electron current component only. This is shown below.



To determine the **electron temperature**, **plasma potential** and **electron density** the natural logarithm of electron current versus probe potential is plotted from this electron current characteristic as shown below.

$$n_e = 3.73x10^{13} \frac{I_{est}(amps)}{A_p(m^2)\sqrt{T_e(eV)}}$$

$$T_e = -\frac{1}{Slope}$$

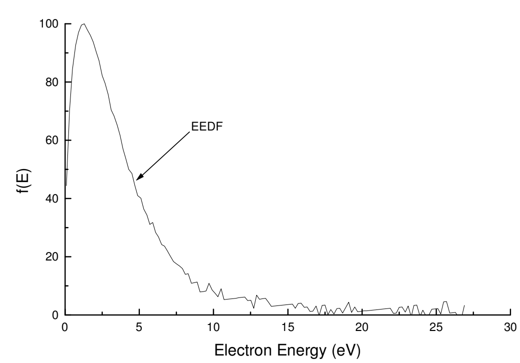


Using the ln(Ie) versus V plot, the **electron temperature** is found by fitting a line to the transition region as shown above and is equal (in units of eV, where 1 eV = 11600K) to the negative inverse of the slope of this line. The **plasma potential** is the probe voltage corresponding to the intersection of the fitted electron saturation and transition lines. To find the **electron density**, the electron saturation current, the electron current at the plasma potential, is used in the equation shown above.

- Electron Energy Distribution Function (EEDF)

The EEDF is determined by the Druyvestyn method which uses the second derivative of electron current with respect to voltage as calculated from the electron current characteristic.

$$f_E(V) = \frac{-4}{A_p e^2}\left(\frac{m_e(V_p - V)}{2e}\right)^{1/2} \frac{d^2 I_e(V)}{dV^2}$$



In the above analysis steps the following variable have been used:

Vf = *Floating Potential*

Vp = *Plasma Potential*

V ***= Probe Electrode Voltage***

A_p = *Probe Area*

M = *Ion Mass*

m_e = Electron Mass

n_I = Ion Density

n_e = Electron Density

I_{esat} = Electron Saturation Current

e = electron charge

I = I_{ion} + $I_{electron}$

I_e = electron current

f_E (V) = electron energy distribution as a function of probe voltage

Appendix I - definitions

- Plasma Potential

The plasma potential is the voltage inside the plasma. It is always positive with respect to the most positive body with which it is in contact. In many cases, the plasma potential provides a good indication of the energy of positive ions incident on surfaces of interest.

- Floating Potential

This is the potential at which an object in contact with the plasma collects no current. Or in other words, the potential attained by an electrically isolated body in the plasma. The separation between the floating and plasma potential are related though the electron energy distribution and ion mass.

- Electron Density

The electron density is simply the number of electrons per unit volume within the plasma.

- Ion Density

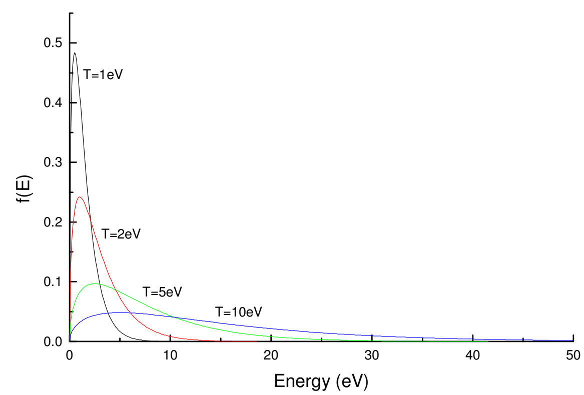
The ion density is the number density of the ions per unit volume within the plasma. Ions can be negative or positive. For an electropositive discharge, all ions formed in the plasma have a positive charge and the ion and electron densities in the bulk of the plasma are equal. For an electronegative discharge, the ions may be either positive or negative, in which case the sum of electron and negative ion densities must equal the positive ion density.

- Electron Temperature

The electron temperature (assuming a Maxwellian distribution of velocities) is the mean energy of electrons in the plasma.

- Electron Energy Distribution Function (EEDF)

In a typical cold laboratory plasma, the electrons are usually much more energetic than the ions and the majority of the energy within the plasma is contained in the electrons. Electrons usually have a spread of energies and knowing the distribution of these energies is of key importance since the electrons are largely responsible for many of the reactions in the plasma. The figure below shows the EEDF of a Maxwellian plasma for several electron temperatures.



Appendix II - Frequently asked questions (FAQs)

The information of the preceding sections provides a general overview of the Langmuir probe technique. The following FAQs and corresponding responses attempt to deal with issues arising in specific applications by describing the features of Hiden's ESP*ION* probe which have been specifically developed.

Q1 *How can the ESPION help me?*

A1 The ESP*ION* provides detailed information about the key parameters in your plasma process. Knowledge of these can assist in identifying processing problems, in designing and troubleshooting new processes and in checking for deviations between chambers.

Q2 *My process uses depositing / etching gases, will the **ESP**ION probe become contaminated and will this affect the results?*

A2 The ESP*ION* probe has been developed with these applications in mind. ESPsoft software enables the active probe tip to be automatically toggled between acquire and clean cycles between individual scans ensuring that data is always acquired with a clean probe tip. Cleaning is achieved by ion bombardment sputtering or by joule heating when collecting an electron current.

Q3 *My plasma is generated with RF voltages, will this affect the measurements?*

A3 In an RF plasma, a significant AC voltage can develop between the plasma and probe tip. The ESP*ION* uses a passive technique incorporating a high frequency compensation electrode together with a string of inductors immediately behind the tip, effectively a tuned LC circuit, in order to remove this AC component and its harmonics. The inductors are air cooled to prevent degradation in hot environments.

Q4 *What type of tip materials are used?*

A4 ESP*ION* can be supplied with many different types of tip materials including Molybdenum, Tungsten, Platinum etc. The tips are easily user interchangeable.

Q5 *My chamber is often coated with insulating materials, does this affect the measurements?*

A5 ESP*ION* employs an integral low frequency reference electrode which compensates for chambers with poor or no ground reference. The reference probe also serves to track and eliminate low frequency noise due to mains/power supply instabilities.

Q6 *Can I use pulsed plasmas?*

A6 Yes. The ESP*ION* probe is capable of making measurements in plasmas which are modulated upto 100 kHz. The gating resolution is 1 microsecond. The complete timing electronics, gating, delay etc. are contained within the ***ESP**ION* control unit and controlled by ESPsoft software so that only the pulse which modulates the plasma is required as an input.

Q7 *Can I make spatially resolved measurements?*

A7 Yes. The ESP*ION* can be supplied with an automated z-drive which is controlled via ESPsoft software allowing data to be taken as a function of position within the chamber.