A Study Of The Use Of an Emissive Probe In a High Pressure Plasma

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

(Nuclear Engineering & Engineering Physics)

at the

University of Wisconsin - Madison

1996

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ABSTRACT

The characteristics of emissive probes in unmagnetized high pressure (≤ 2 Torr) argon and helium plasmas produced by inductively coupled 13.56 MHz RF power are studied. A procedure is given for interpreting emissive probe current-voltage (I-V) characteristics. The I-V curves indicate the amplitude of the RF fluctuation of the plasma potential. They also show ionization near the emissive probe when the potential drop between the emissive probe and the plasma potential is more than the ionization potential. Experiments show that when the temperature of the emissive probe wire and/or the neutral pressure is increased, ionization becomes significant. An increase in the local ion density due to the additional ionization was demonstrated by the I-V curves of a nearby Langmuir probe. A simple procedure is presented for interpreting these results.

ACKNOWLEDGMENTS

I am very grateful to Professor Noah Hershkowitz for his theoretical direction and continuous encouragement throughout the experiments and for his critical reading of the manuscript; to Husain Kamal and Jay Amundson for their excellent technical assistance and discussion; to James Dekock, Gon-Ho Kim and Paul Probert for their generous help.

I INTRODUCTION

The plasma potential is an important parameter in most plasma experiments. The I-V characteristic curves of Langmuir probes depend on both the plasma potential and the electron velocity distribution function. When electron tails, plasma drifts, or RF is present in the plasma, the floating potential of a Langmuir probe is no longer indicative of the plasma potential. [1] On the other hand, emissive probes have been demonstrated to provide a reliable measurement of the plasma potential at low pressure, ($<$ 10mTorr) in the presence of electron tails, plasma drifts and RF. [2, 3, 4]

An emissive probe is essentially a hot wire probe (commonly tungsten), heated sufficiently to allow thermionic emission of electrons and biased with respect to the plasma potential. When the bias voltage V_b of the probe is more negative than the local plasma potential V_p, electrons which leave the probe can escape to the plasma and appear as an effective ion current. When the probe is biased more positive than the local plasma potential, electrons emitted from the probe are reflected back to the probe. Using this effect, it has been shown how to determine the plasma potential at the emitting probe wire to an accuracy the order of T_w/e [7], where T_w is hot wire temperature. This process is not sensitive to plasma flow because it depends directly on plasma potential rather than electron kinetic energy and it is also less sensitive to probe surface contamination when heated surfaces provide electron emission.

In order to simplify the description of emissive probe characteristics, weakly emitting probes can be considered first. Neglecting space charge effects, the emissive current I_e from a hot wire can be approximately written as [9]

$$I_e = I_{eo} \exp \left[\frac{-e(V_b - V_p)}{T_w}\right] g\,(V_b - V_p), \qquad V_b > V_p \qquad (1)$$

$$= I_{eo} \qquad V_b < V_p \qquad (2)$$

Where I_{eo} is the electron emission saturation current. The quantity $g\,(V_b - V_p)$ accounts for the orbital angular momentum and depends on the hot wire radius and on the sheath radius. The emission current appears as an apparent ion collection current. The probe also collects electron and ion currents I_c from the plasma. Neglecting space charge effects, the contribution to I_c from Maxwellian plasma electrons with temperature T_e can be written as [9]

$$I_c = I_{co} \exp \left[\frac{-e(V_b - V_p)}{T_e}\right], \qquad V_b < V_p \qquad (3)$$

$$= I_{co}\ f\,(V_b - V_p), \qquad V_b > V_p \qquad (4)$$

Where $f(V_b - V_p)$ again takes into account orbital effects, and Ico is the probe saturation collection current. Ideal emitted and collected currents are indicated in Fig. 1. when the probe radius << sheath thickness, space charge is neglected and the plasma potential V_p has been set equal to 0 V. [9]

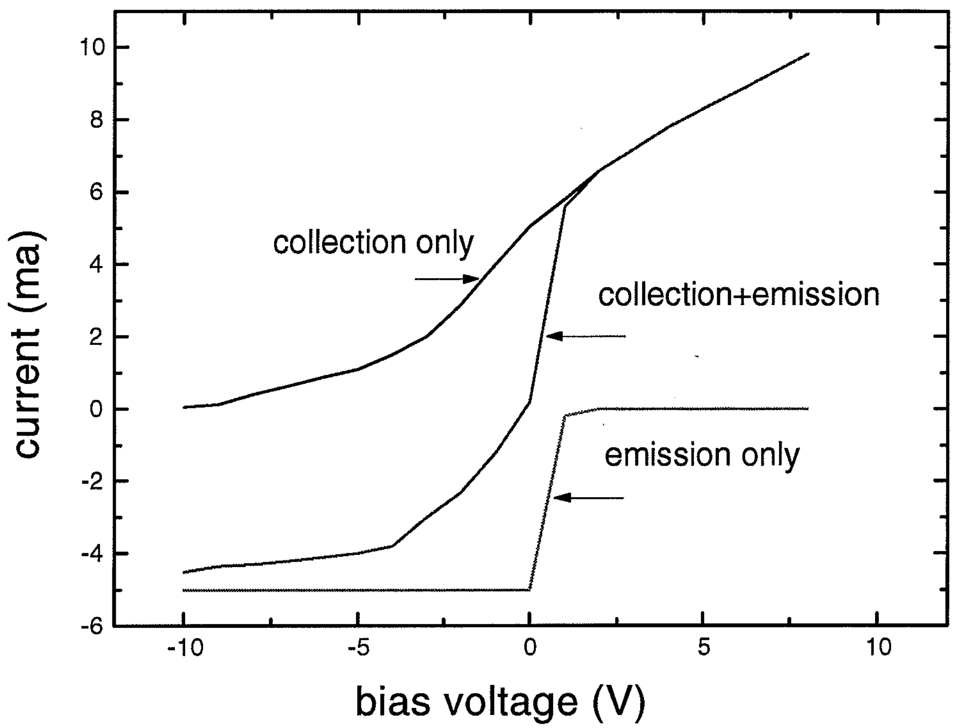

Fig. 1. Collecting and emitting I-V characteristics for a cylindrical wire probe in a plasma. The electron and wire temperatures are T_e =3eV, T_w = 0.3eV.

The characteristic of an emissive probe was first discussed by Langmuir. [12] A technique has been described for obtaining an approximation of the plasma potential from the floating potential of a strongly emitting probe with $I_{eo} / I_{co} >> 1$ by Kemp and Sellen. [5] More recently it has been shown that several methods are available for using emissive probes. [4,15, 7, 16] These methods include the inflection point method in the limit of zero electron emission, [6] differential emissive probes, [4] emissive capacitive probes which depend on secondary electron emission, [16] and self emissive probes [17].

It is found that the probe floating potential moves toward more positive potentials as the emissive probe is heated. [14] The significant electron emission is also likely to produce perturbation. [5] [13] A procedure which has gained some acceptance is given by Chen. [3] He suggests that the bias voltage at which hot and cold probe characteristics separate should be taken as an indication of the plasma potential. However, since this procedure makes use of cold probe characteristics, it is subject to large errors resulting from contamination of cold probe surface.

However, as the gas pressure is increased in a weakly ionized plasma, there is a strong tendency for a current discharge to be established near the probe. Strongly heated emission probes can heavily perturb the local potential near the probe, and in addition, the emissive probe can melt. An advance over the floating potential technique is the inflection point method of interpreting an emissive probe[7] at low pressure. The basic idea of the inflection point technique is the space charge effects associated with the emitted electrons go to zero in the limit of zero electron emission. The inflection point is determined with high accuracy by differentiation of the emissive probe I-V curve.

In addition, it has been shown the potential difference between two peaks in the differentiated I-V trace of an emissive probe can be used to give a good indication of the fluctuation in the plasma potential. [6] Recently, it has been reported [8] that a potential structure at the crest and trough phases in a RF oscillation near a powered electrode can been observed and the sheath thickness from the RF electrode surface can been estimated using the emissive probe technique given in ref.6.

In practice, because the peak of the derivative dI / dV_b is often small compared to noise and operational amplifier turn-on transients, the inflection point is normally distinguished by its variation with changing emission voltages in determining the inflection point in the limit of zero emission. [7] At pressures greater than 0.2 Torr, ionization effects make it more difficult to distinguish the inflection point in the limit of zero emission. To date, measurements have only been carried out at low pressure using this method because of uncertainties in the use of the technique at higher pressure. In this thesis, a technique is presented to detect plasma potential at pressure as high as 2 Torr. Using this technique we have also studied the effect of RF power and the neutral pressure on the plasma potential, electron temperature and density.

II APPARATUS AND PROCEDURE

The experimental apparatus is shown in Fig. 2. The relative position, orientation and size of the electric probes are also presented. The system consists of a cylindrical vacuum chamber with a roughing pump. The neutral gas pressure in the chamber was varied from 10 mTorr to 2 Torr. A one turn ring antenna in the vacuum chamber is insulated from the plasma with fiber glass. The 13.56 Mhz RF power supply is connected to the antenna using a capacitive matching circuit which is adjusted to minimize the reflected power.

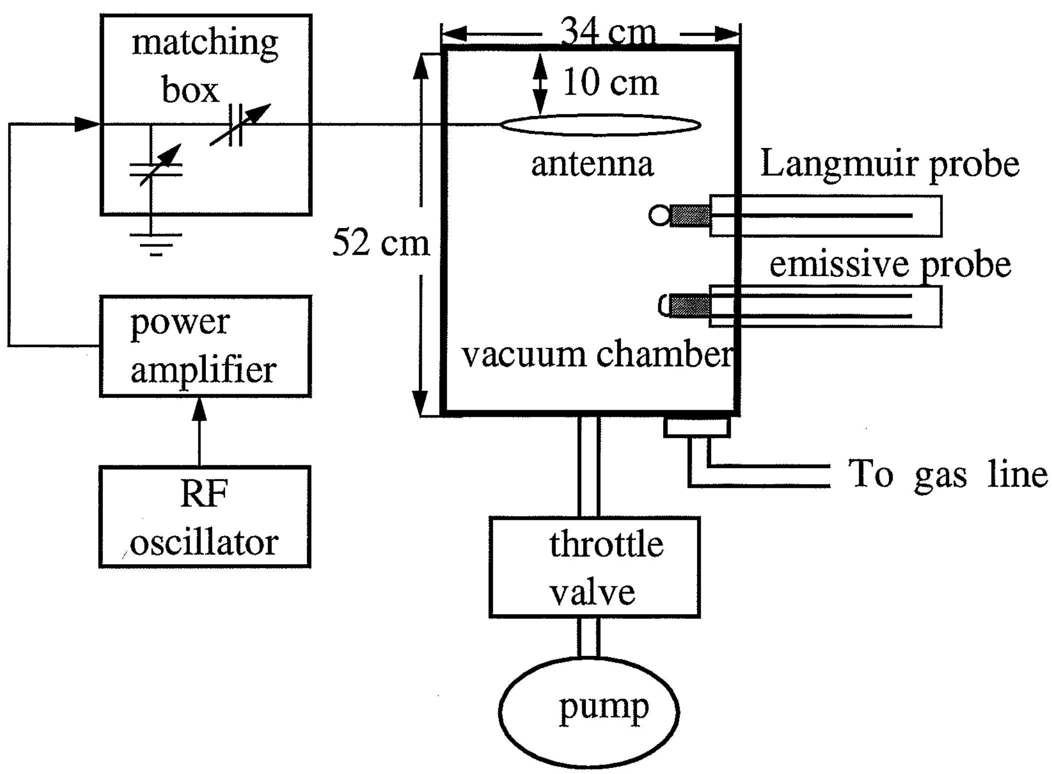

Fig. 2. Experimental setup.

A movable Langmuir probe with a 1/4 inch diameter one-sided disc was used to measure the I-V characteristic curve. The I-V curve was then used to calculate the basic parameters of the plasma. The filaments of the emissive probe are of thoriated tungsten, 0.0025cm in diameter and 0.5 to 1.0cm long. The filaments are spot-welded to gold coated copper wires and insulated with ceramic. The probe shafts are constructed of 8 mm stainless steel tubing with coaxial ceramic tubing for insulation. BNC connectors are used for the emissive filament heating and bias voltage V_b connections. Vacuum sealing is provided by an o-ring at the chamber wall.

A schematic diagram of the circuits used for this study is shown in Fig. 3. A DC heating current was supplied by a floating power supply which consisted of an isolation amplifier with a buffer output as shown in Fig. 4. The heating voltage could easily be controlled by increments of 0.01V at the D/A output channel. Both the heating voltage and bias voltage of the emissive probe were computer controlled. Another D/A output channel was used to produce a sawtooth voltage with a range of -5V to +5V , which was amplified by a Kepco operational power supply to be -100V to +100V. A resistor voltage divider was used to transfer the partial sweep voltage to an A/D input channel to monitor the actual sweep voltage. A current sampling resistor with a capacitance filter was used to convert the probe current to voltage and to transfer the collected voltage to another A/D input channel. This setup allowed real time data collection.

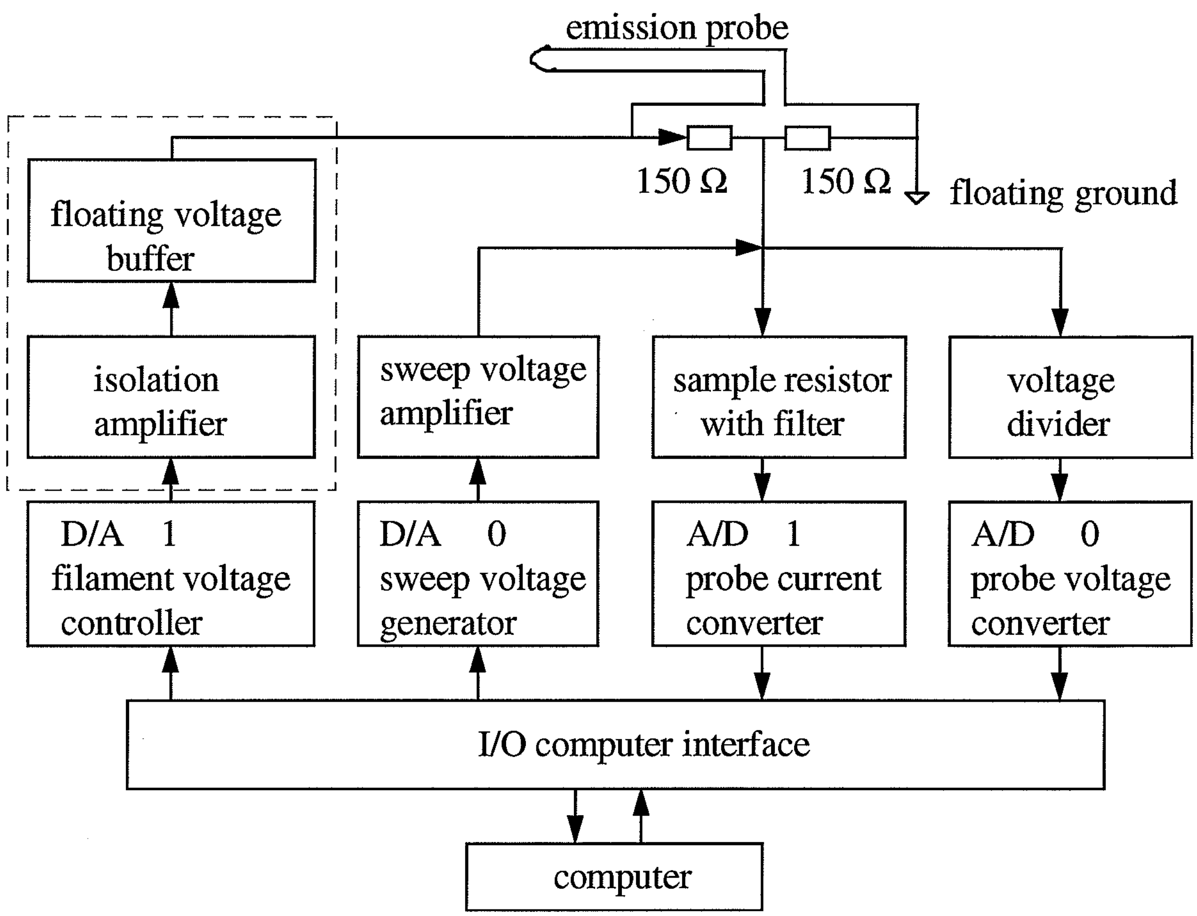

Fig. 3. Schematic diagram.

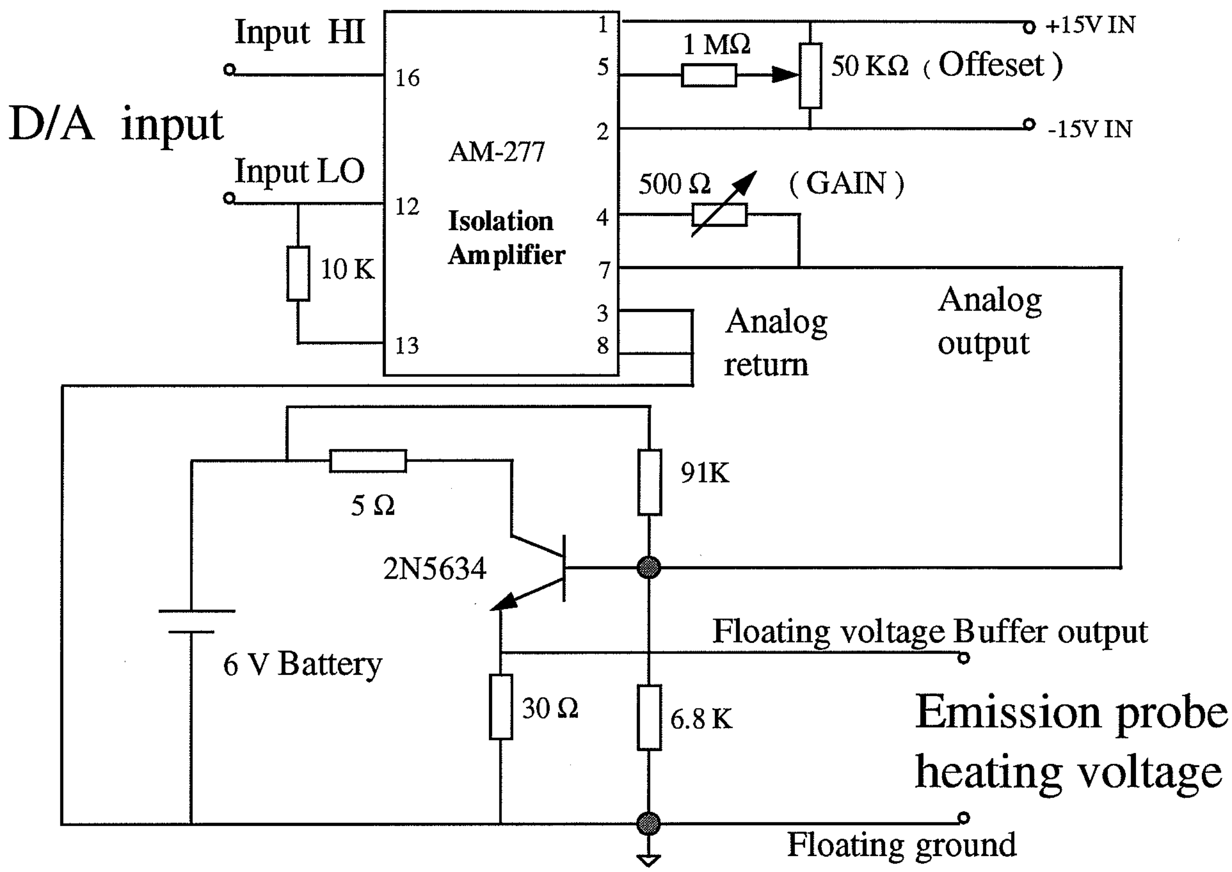

Fig. 4 Emission probe heating circuit.

The data were extracted and corrected by a data processing program. The procedure was (1) Collecting the I-V data with RF plasma. (2) Collecting the I-V data without RF power (i.e. the load line). (3) Smoothing both sets of data. (4) Determining the slope and the shift of the load line. (5) Reproducing the "pure" I-V curve by subtracting the load line data. These data were reproducible and gave a reliable measurement of the probe I-V characteristics.

The same circuits and procedure was used to obtain the I-V curve of a collecting Langmuir probe (without supplying a heating voltage). From a semilog I-V characteristic plot, the electron temperature was determined from the slope of the I-V curve near the knee at the minimum value of the fluctuating plasma potential. This requires identification of the minimum value of the plasma potential. Once the temperature and ion saturation current were known, the plasma density was calculated using the Bohm current formula. [10]. Our data processing program can also be used to automatically find ion saturation current and calculate electron temperature and electron density based on the bias voltage range of the I-V curve. Details of the real-time data detection program and data processing program are given in the appendix.

III RESULTS AND DISCUSSION

In order to avoid disturbance from strong emission, we first use a weakly emitting probe and assume that space charge effects are not important. A representative I-V trace of an emissive probe in argon plasma at 0.5 Torr neutral pressure for small RF power (10W) is shown in Fig. 5.

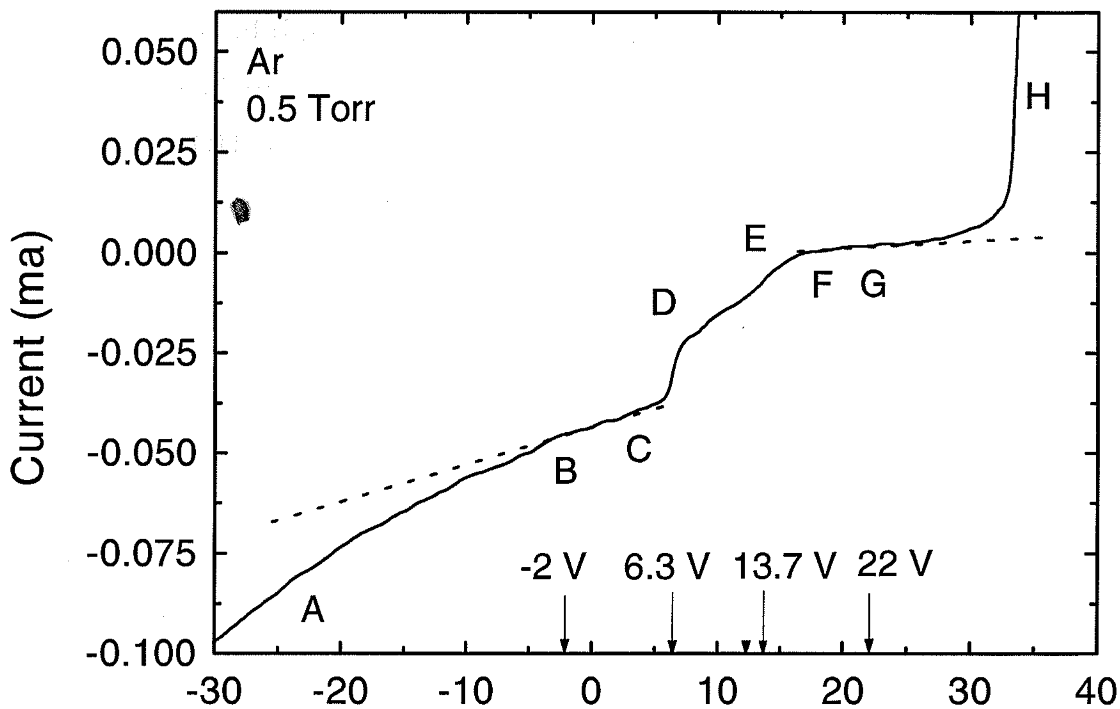

Fig. 5. The I-V curve of the emissive probe for Ar plasma at 0.5Torr.

The data exhibit a number of features. The points D and E are obtained from the differentiated I-V trace corresponding to Fig. 5, given in Fig. 6. The segment DE is of major importance. It represents the plasma potential fluctuation amplitude. The midpoint of D and E gives a time averaged plasma potential. The linear segments FG and BC have been identified as the electron saturation current and the temperature limited emissive current respectively. These emissive probe characteristics generally can be found at low pressure. The non-linear segments GH and AB are more interesting phenomena in high pressure discharges. Both lines deviate from the continuation of lines FG and BC (which are shown as dashed lines) can be explained as ionization currents. The points B and G are from the onset of ionization. GH is produced when the emissive probe is biased to a sufficiently large positive bias and AB occurs when it is biased to a sufficient negative bias with respect to the plasma potential. The midpoints of B and G also gives a time averaged plasma potential which is in agreement with the value determined by the inflection point method.

The details of the differentiated curve in the region between C and F are shown in Fig. 7. These data resemble data shown in ref. 3 and allow identification of the difference voltage between the two peaks as a measure of the plasma potential fluctuation amplitude. [7] This hypothesis was checked by varying the RF power. As seen in Fig. 8, the difference between the two peaks increases approximately linearly with increasing RF power (with a zero power intercept approximately equal to zero).

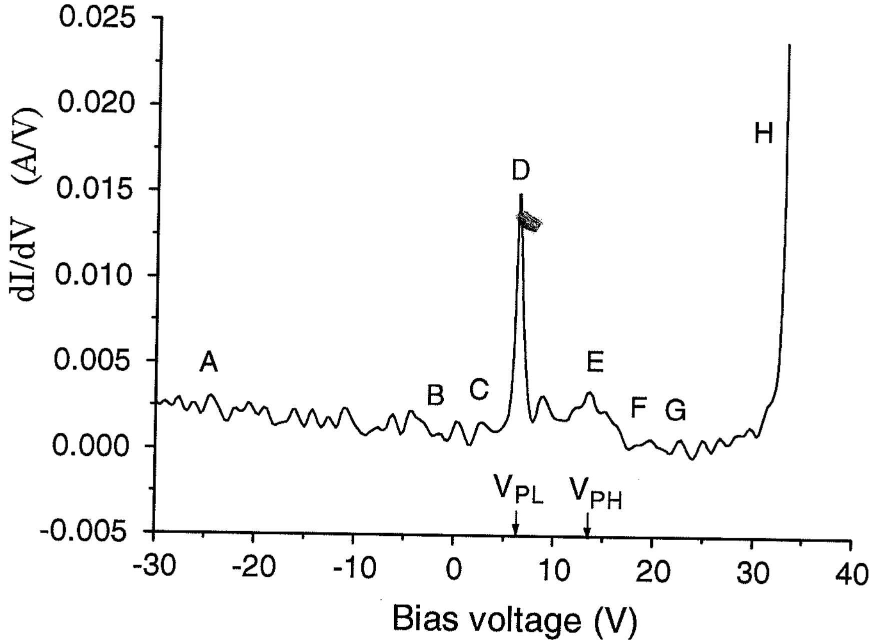

Fig. 6. The derivative of the current vs. voltage of the data given in Fig. 5.

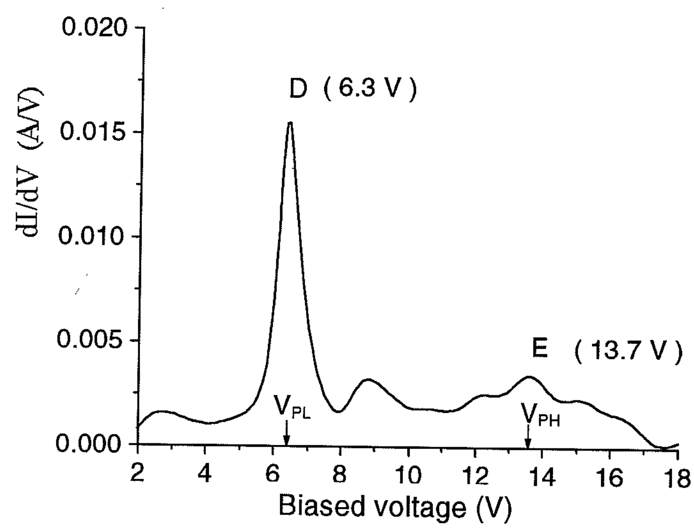

Fig. 7. A selected range of the I-V curve in Fig. 6. Notice the fluctuating plasma potential V_{PL} and V_{PH}

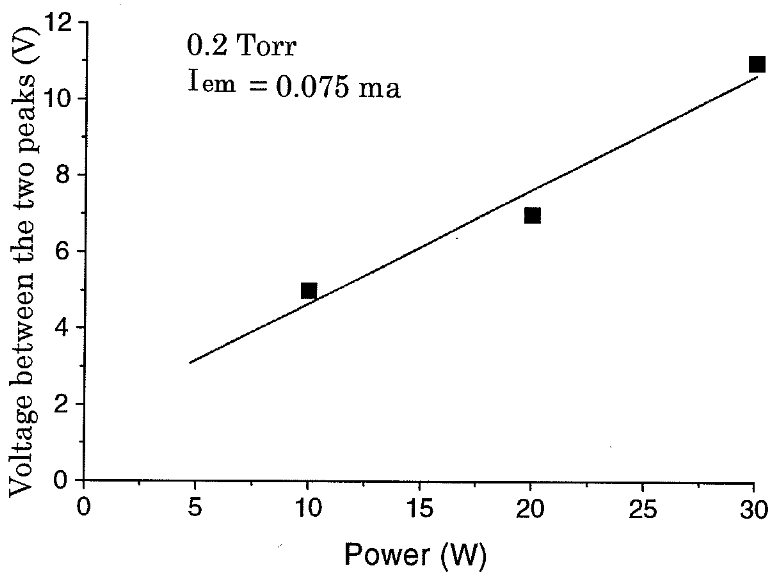

Fig. 8. The voltage between V_{PH} and V_{PL} of the emissive probe as a function of RF power.

The variation in the inflection point potential with emission current for RF power 15W at neutral pressure of 0.5Torr is given in Fig. 9. These data show that as emission is decreased, the upper (V_{PH}) inflection point moves to higher potentials while the lower (V_{PL}) inflection point moves to lower potentials. The time averaged plasma potential, defined as the potential midway between the two inflection points, is approximately constant with emission current. Also note, the probe behavior shown in Fig. 9 is similar to those previously found at much lower pressure[7].

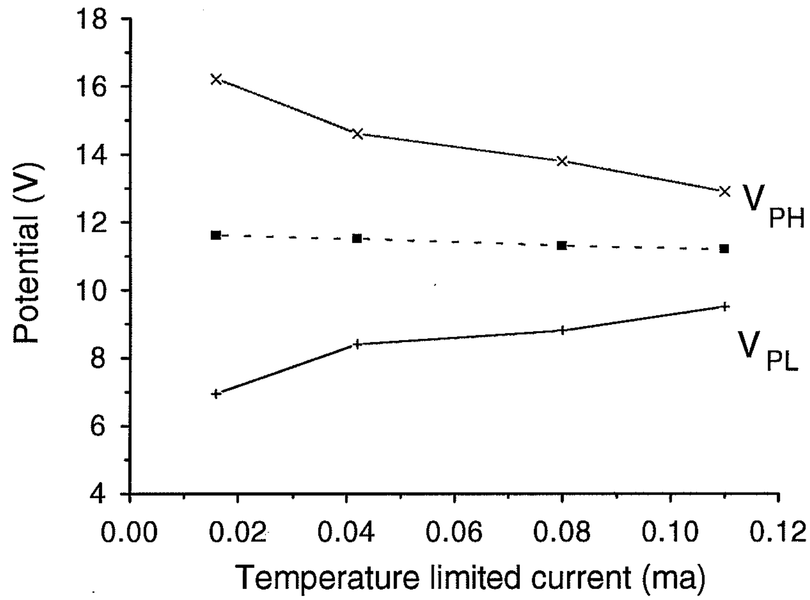

Fig. 9. The change in the plasma potential as a function of the increase in the temperature limited current.

For the data shown in Fig. 7, the minimum plasma potential V_{PL} of peak D is 6.3 V, and the maximum plasma potential V_{PH} of peak E is 13.7 V. Therefore, the amplitude of the fluctuation is approximately 7V. The midpoint of these two peaks (10V) is the time averaged plasma potential V_P . [7] Our experimental data also indicate that the time averaged plasma potential increases with increasing sinusoidal RF power. In Fig. 10 the two curves represent the results for argon plasmas at neutral pressures of 0.1 Torr and 0.75 Torr respectively. The data in Fig. 10 show that the plasma potential becomes more positive as the neutral pressure increases for the same RF power.

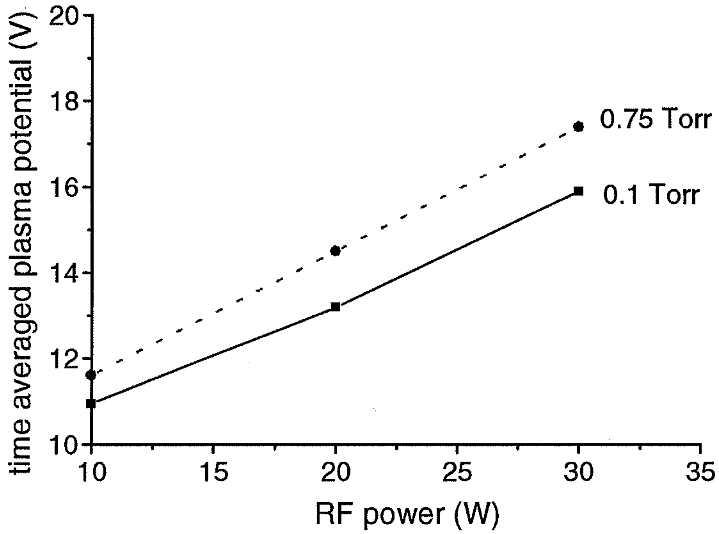

Fig . 10. Time averaged plasma potential as a function of the RF power

Fig. 5 also shows that segments FG and GH, with bias voltages $V_b > V_{pH}$, contain contributions from the electron collection current. The plateau segment FG corresponds to the usual probe electron saturation current. However, the electron current is observed to increase as the positive bias voltage is increased. This is plotted as segment GH. This increase in electron current can be explained by additional ionization when the bias voltage is more positive than the minimum value V_{pL} of the fluctuating plasma potential. The onset of ionization occurs at a bias voltage of approximately 22V at G, while the minimum fluctuating potential is approximately 6.3V. The difference in potential is then approximately equal to the ionization potential of the argon gas (15.8 V), so plasma electrons can acquire enough energy to ionize the gas in going from the background plasma to the probe.

Electron emission is not critical to the sudden increase in electron current seen with emissive probes as shown in Fig. 5. In fact, the same phenomenon was observed in the I-V trace of a Langmuir probe as shown in Fig. 11. The experimental conditions are approximately the same as in Fig. 5. Note that again the current begins to increase at approximately 22V.

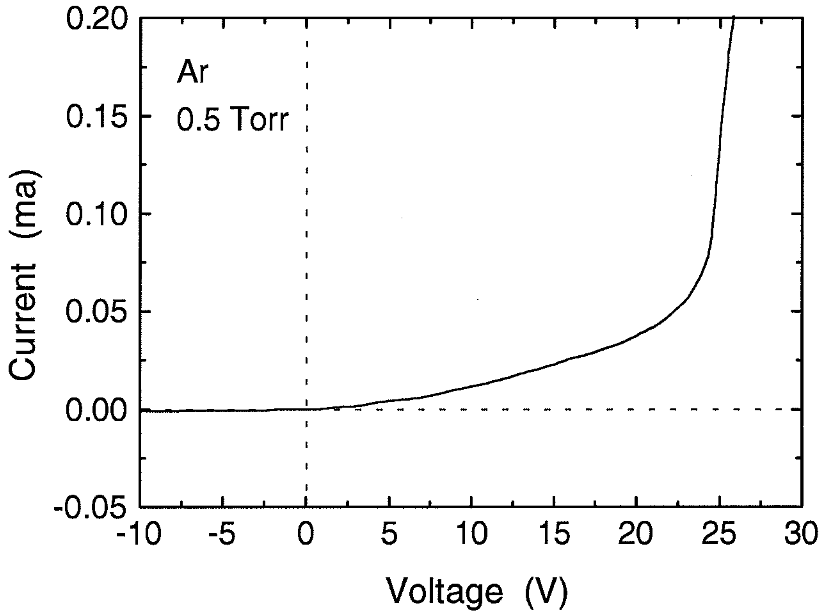

Fig. 11. I-V curve of the Langmuir probe

When the Log(I) is graphed vs bias voltage V_b (see Fig. 12), knees are apparent at about 6.3V and 26V. The lower knee corresponds to the minimum plasma potential V_{pL} (labeled D in Figs. 5-7) identified by the emissive probe. The knee at around 26V can then be identified as a consequence of ionization as it was for the emissive probe.

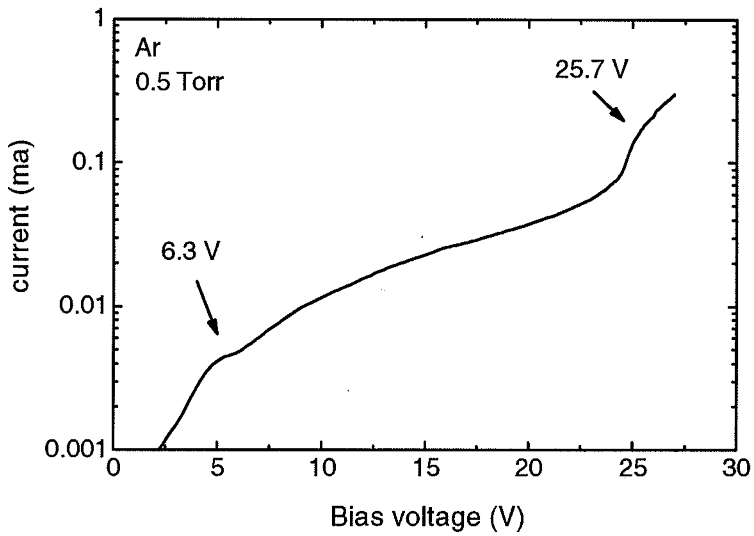

Fig. 12. Semilog plot of the Langmuir probe I-V curve in Fig. 11.

By fitting a line to the slope of log (I) vs V_b on the semilog plot Fig. 12, the electron temperature can be calculated using: [9]

$$T_e = e\frac{dV_b}{d\ln(I)} \qquad (5)$$

The plasma electron density was determined from the ion saturation current (see Fig. 13) using: [9]

$$I_i = \frac{1}{2}n_e A\sqrt{\frac{T_e}{m_i}} \qquad (6)$$

Here I_i is the ion saturation current, n_e is the electron plasma density, T_e is the electron temperature, A is the probe disk area, m_i is the ion mass. The electron temperature and the electron density are 1.4 eV and 2.1×10^8 cm^{-3} respectively for Fig. 5 and Fig. 12.

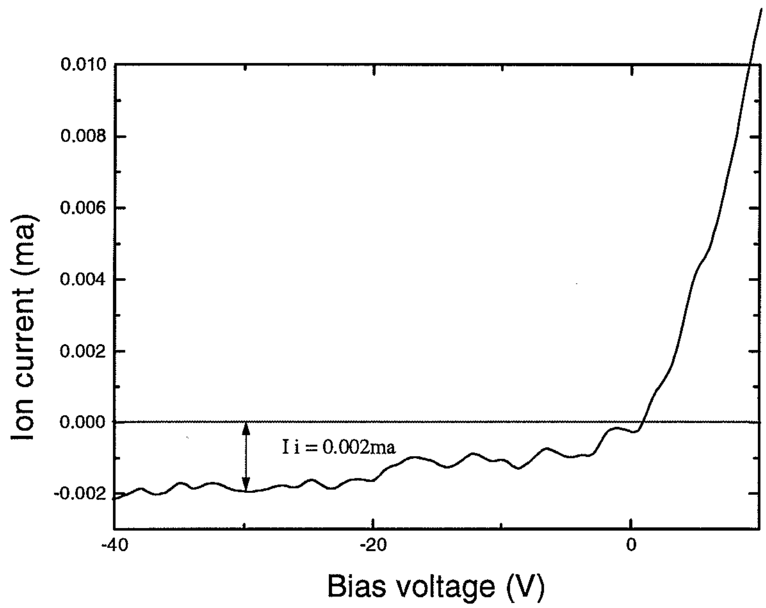

Fig. 13. A detail of the Langmuir probe I-V curve in Fig. 11

In this way, we also measured the electron temperature and the electron density as a function of neutral gas pressure, at the center of the chamber, (see Fig.'s 14 and 15). Fig. 14 shows the electron temperature decreases with increasing gas pressure. Fig. 15 shows that the electron density increases with increasing gas pressure.

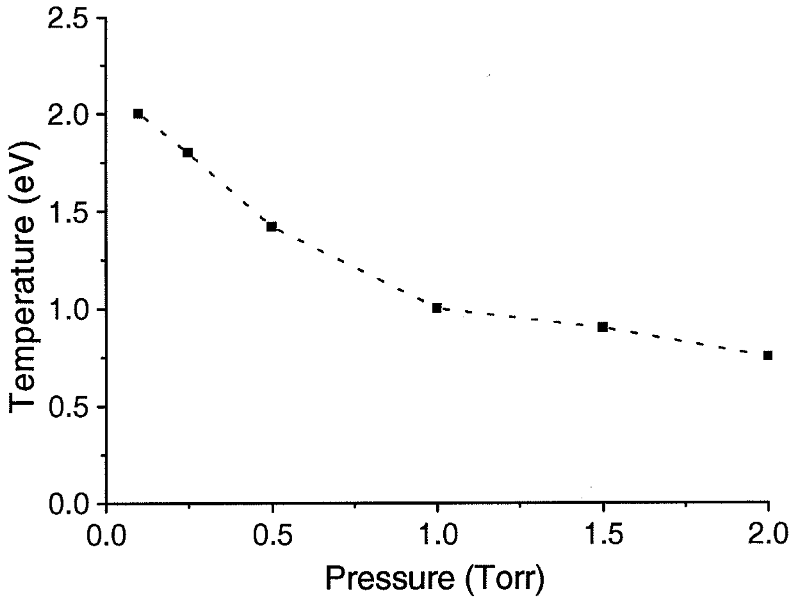

Fig. 14. Electron temperature of Ar plasma as a function of pressure.

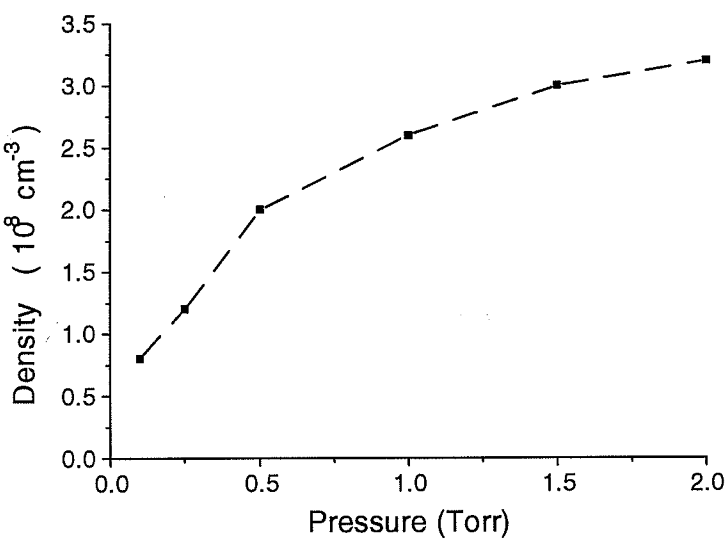

Fig. 15. Electron density of Ar plasma as a function of pressure.

In Fig. 5, a short straight line BC for a temperature limited emissive current is observed. This is due to the finite wire temperature. However, it was observed that the emissive probe current was not limited when the emissive probe was biased more negatively. When the emissive probe was biased negative with respect to the maximum plasma potential (13.7 V), by an amount greater than the ionization potential of argon ($\varepsilon_i = 15.8V$), additional ion current from ionization was produced shown as segment AB in Fig. 5. Also in Fig. 5 the onset of ionization was at approximately -2 V at B.

Therefore the presence of the onset of ionization for both positive and negative bias voltages provides another way to determine the time averaged plasma potential with an emissive probe. In Fig. 5 the midpoint of B and G gives a time averaged plasma potential $V_P = 10V$, in agreement with the value determined by the inflection point method with D and E in Fig. 6.

When the emissive probe is biased negatively with respect to the V_{PH}, the electrons emitted from the filament are accelerated to the plasma potential. This gives the electrons sufficient energy to ionize the background gas if the potential difference exceeds the ionization potential. The ionization is restricted to a region within the order of the ionization mean free path λ_i. At high neutral pressure, the size of this region can become comparable to the sheath dimension. The ionization increases the plasma density near the emissive probe with a corresponding increase in the ion saturation current to the probe. The ion saturation current also increases with the emissive probe wire temperature. Fig. 16 and Fig. 17 show I-V characteristics of an emissive probe at four probe temperatures for helium and argon plasmas respectively. When the temperature of the wires increases, the ionization becomes significant at smaller negative bias voltages. The data also show that the onset of ionization occurs at a lower bias voltage in argon than in helium, consistent with the ionization potential ε_ι of argon and helium gas (15.8 eV and 24.6 eV respectively) [11].

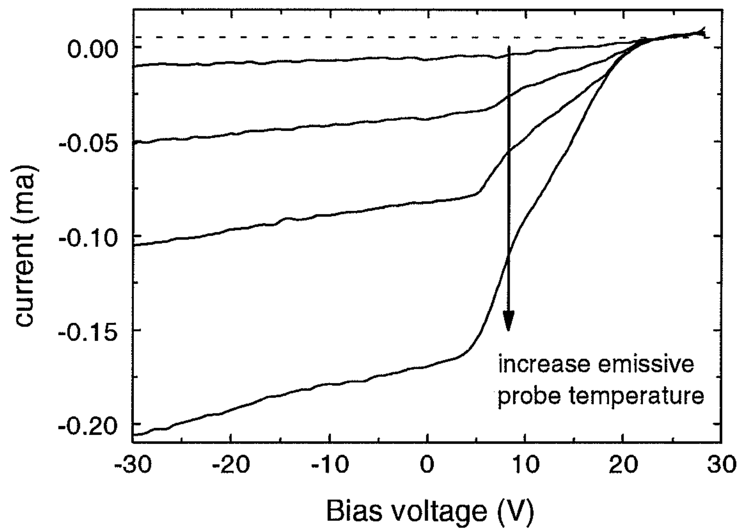

Fig. 16. I-V curve of the emissive probe for Helium plasma at four probe wire temperatures.

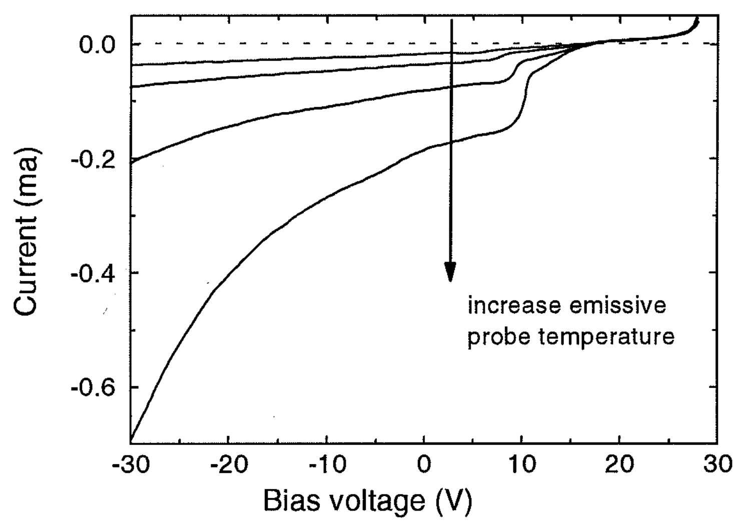

Fig. 17. I-V curves of the emissive probe for Argon plasma at four probe wire temperatures.

Fig. 18 shows the I-V curves of an emissive probe at approximately the same wire temperature but at different pressures. These curves correspond to approximately the same temperature limited emissive current (I_{em}) with different ionization currents (ΔI_i). The ionization currents all increase with neutral pressure when the emissive probe is more positively or negatively biased than the ionization potentials ($\varepsilon_i = \pm$ 15.8V for argon gas) with respect to the plasma potential. It is apparent that the I-V curves of the emissive probe are not symmetric at positive and negative bias voltages.

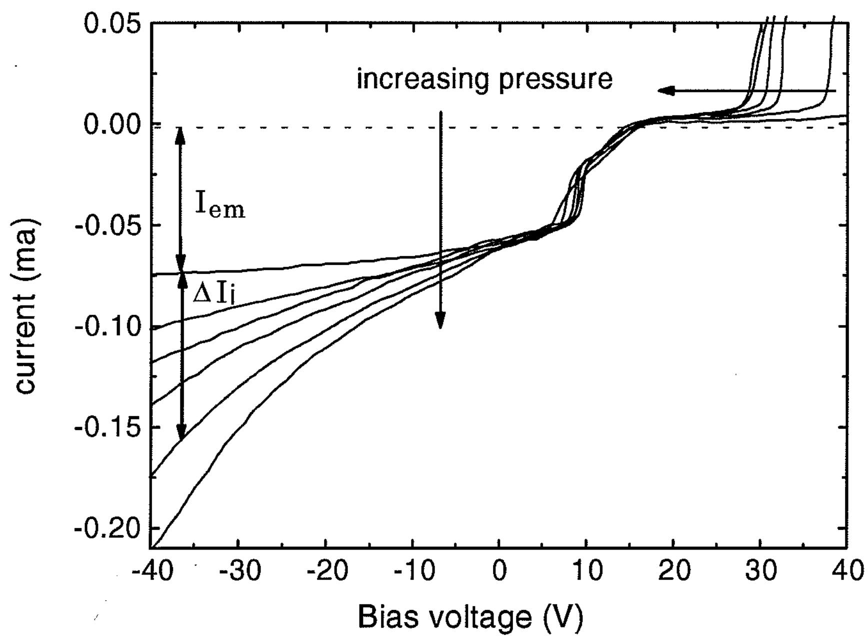

Fig. 18. I-V curves of the emissive probe with the same wire temperature but at different pressures (0.05 - 1 Torr).

The asymmetry is present because the ionization currents have different origins. Although both increases are the result of increased ionization, the increased negative current in the negative bias ionization region is due to extra ion current, while the increased positive current in the positive bias ionization region is due to increased electron collection. In addition, the ionization takes place in different locations. For the negative bias, electrons emitted at the probe are the source of the additional ionization. For the positive bias, the additional ionization takes place within the sheath where plasma electrons gain energy as they accelerate towards the probe wire.

In the negative bias case, the enhanced ionization rate due to the emitted electrons is in the order of I_{em}/e. Since sufficient energy is not available for multiple ionization per electron and the ionization takes place within a region the order of one mean free path λ_i of the emissive probe wire. Ions are lost at the sheath boundary and at the boundary of the enhanced ionization region, with loss rates given approximately by $\Delta n c_s \pi s L$ and $\Delta n c_s \pi \lambda_i L$ respectively, see Fig. 19. Here s is the sheath length, L is the wire length, Δn is the enhanced ion density and c_s is the ion sound velocity.

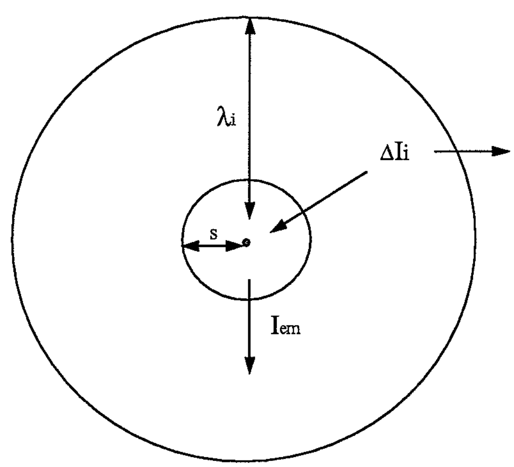

Fig. 19. A schematic of the region near the emissive probe wire at high pressure.

The total particle flux is still conserved. In equilibrium, the total ion loss current equals I_{em}. The total current I is given by

$$I = I_{em} + \Delta I_i \qquad (7)$$

where, I is the measured current by the emissive probe, I_{em} is the emitted electron current and ΔI_i is the portion of ion current (due to the ionization by I_{em}) collected by the probe rather than lost to the outer boundary of the ionization region, as in Fig. 19. Assuming that most of the ionization takes place outside the sheath (assuming $s << \lambda_i$), the increased ion current ΔI_i was given by

$$\Delta I_i = 2\pi\, s\, L\, I_{em} / 2\,\pi\, (s+\lambda_i)\, L \approx I_{em}\, s / \lambda_i = I_{em}\, s\, n_o\, \sigma(\varepsilon) \qquad (8)$$

where,

$\varepsilon = e(V_{PH} - V_b)$ $\qquad$ $Vb < 0$

$\varepsilon = e(V_b - V_{PL})$ $\qquad$ $Vb > 0$

where n_o is the neutral density and $\sigma(\varepsilon)$ is the ionization cross section at electron energy ε. From Eq. (8), we note that the enhanced ion current ΔI_i is proportional to $1/\lambda_i = \sigma(\varepsilon)\, n_o$. If the pressure is increased, λ_i becomes smaller and ΔI_i increases as in Fig. 18 . This is because ionization occurs closer to the sheath, therefore a larger fraction of the ions fall through the sheath.

From Eq. (8), we note that that the enhanced ion current is proportional to $1/\lambda_i = \sigma(eVb)\, n_o$. This dependence can be demonstrated by the portion of the curves in Fig. 18 corresponding to the enhanced ion current by the corresponding values of $\sigma(eV_b)\, n_o$. The results given in Fig. 20 show that all curves coalesce to a single curve corresponding to the lowest pressure in Fig. 18. This demonstrates the additional current is proportional to σ (eV_b) n_o assuming the bulk electron temperature keeps constant during emission.

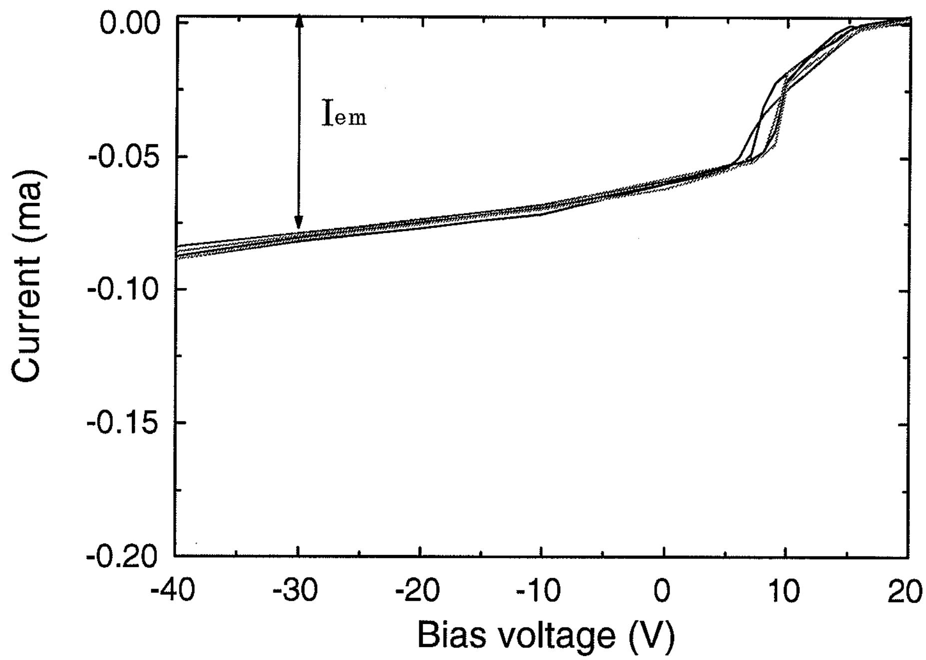

Fig. 20. The emissive probe I-V curves after dividing each of the curves in Fig. 18 by the appropriate n_o $\sigma(\varepsilon)$.

On the other hand, when the probe is strongly biased positive, the plasma electrons inside the sheath have higher electron energy than that outside the sheath. The additional ionization occurs inside the sheath region. This process produces significant ionization if the λ_i is comparable to the sheath thickness. The electrons from the enhanced ionization are directly collected by the positively biased probe. Thus, ionization effects are more apparent at positive bias.

The increase of the plasma density near the emissive probe, due to the ionization, is measured by a nearby Langmuir probe. The changes in the I-V curve of the nearby Langmuir probes for argon and helium plasma with different negative bias voltages, applied to the emissive probe, are shown in Fig. 21 and Fig. 22 respectively. The data show a larger required potential difference for He compared to Ar because of the difference in the ionization potential.

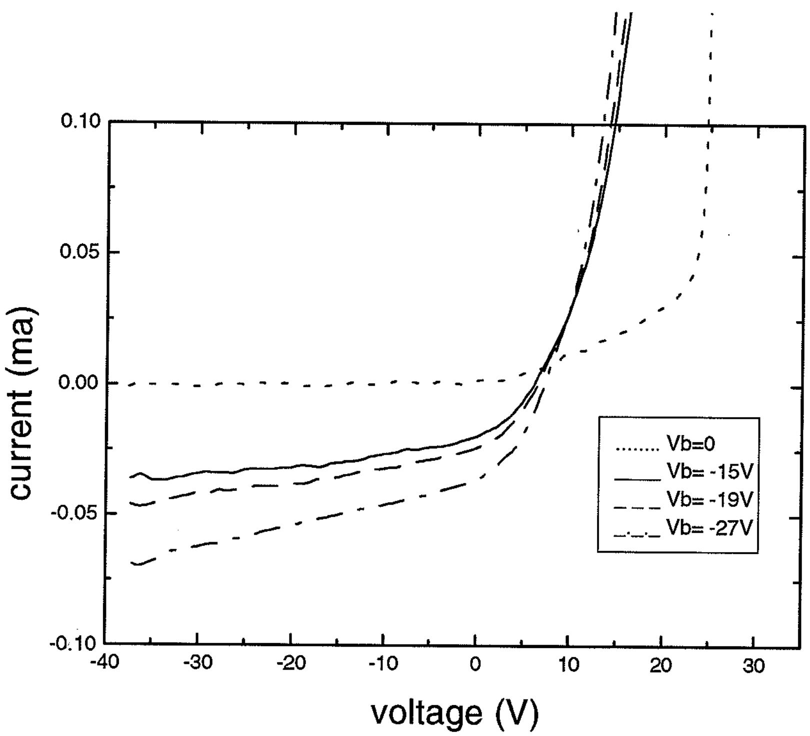

Fig. 21. The I-V curve of the Langmuir probe near the emissive probe ($\approx$ 1 cm) for Ar plasma, the I_i increase as the V_b of the emissive probe becomes more negative.

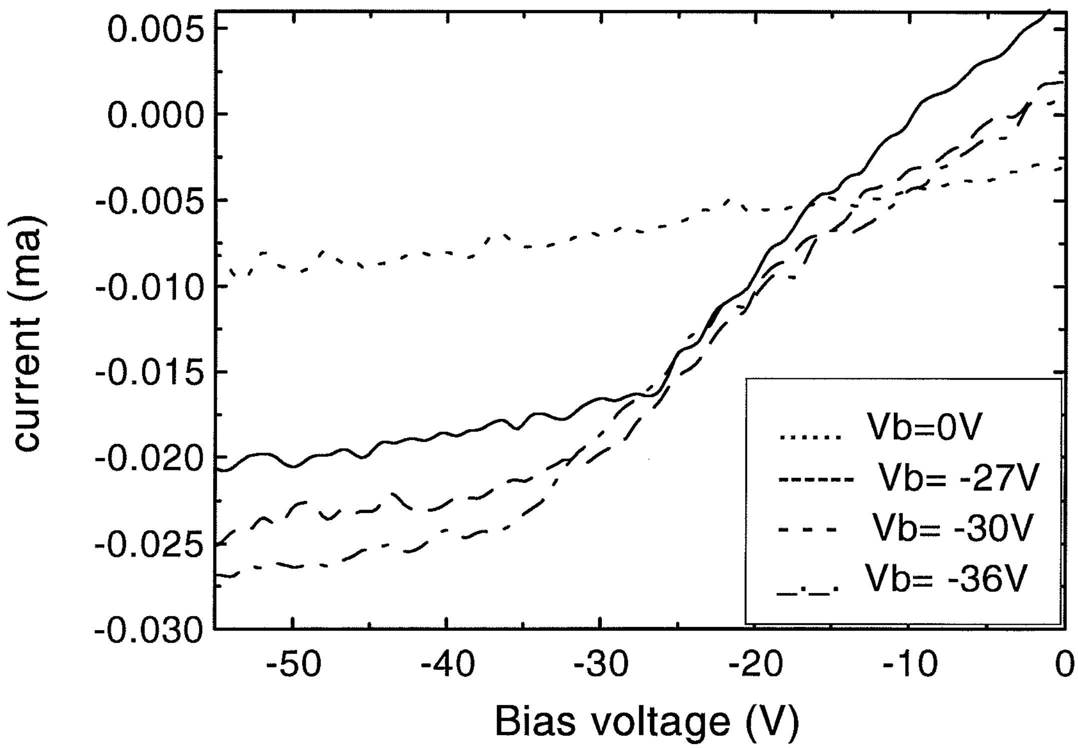

Fig. 22. The I-V curve of the Langmuir probe near the emissive probe ($\approx$ 1 cm) for He plasma, the I_i increase as the Vb of the emissive probe becomes more negative.

Fig. 23 compares the increase in the ion current ΔI_i for argon plasma, measured by the emissive probe, to the ion saturation I_{sat} current measured by the nearby Langmuir probe. Fig. 24 is the same as Fig. 23 but for helium gas. Thus, it is apparent that the increase in ion current at the emissive probe is a result of an increase in the local ion density.

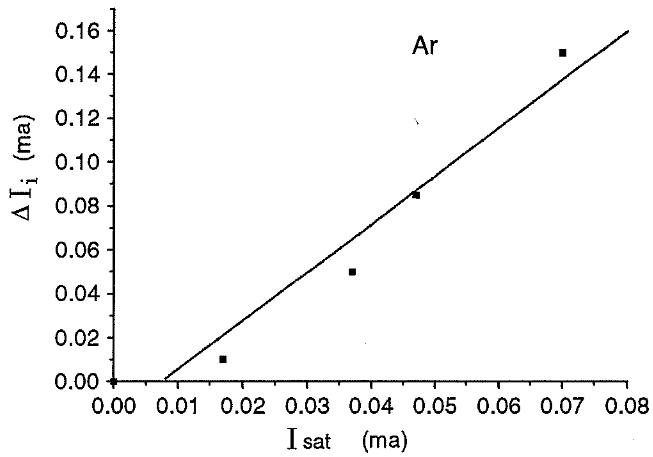

Fig. 23. The ion saturation current measured by the Langmuir probe, near the emissive probe ($\approx$ 1 cm), as a function of the increase in the ion current measured by the emissive probe for Ar plasma.

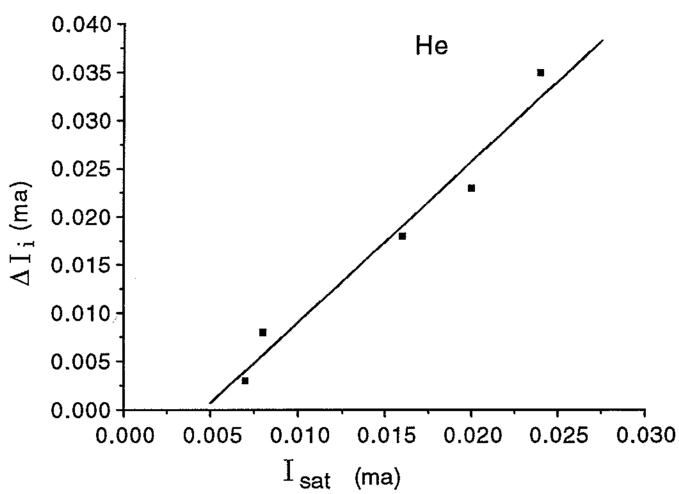

Fig. 24.. The ion saturation current measured by the Langmuir probe, near the emissive probe ($\approx$ 1 cm), as a function of the increase in the ion current measured by the emissive probe for He plasma.

Because of the presence of ionization, emissive probes at high pressure provide several techniques to determine the plasma potential. These include fluctuating plasma potential from inflection point method and also from the onset of ionization.

IV CONCLUSION

We have presented experimental results on the current-voltage characteristics of emissive probe in high pressure plasma, which can be used to measure plasma potential in the presence of RF fluctuations. The time averaged plasma potential significantly increases as the RF power increases and slightly increases with neutral pressure increases. Two portions of the emissive probe I-V characteristic curve in high neutral pressure plasma can be interpreted as local ionizations near the emissive probe. This occurs when the probe is negatively or positively biased by an amount approximately equal to the ionization potential (15.8eV for Ar and 24.6eV for He) with respect to the plasma potential. The presence of ionization provides emissive probes at high pressure with a technique for determining the plasma potential from the onset of ionization. Using a combination of Langmuir and emissive probes, both the electron temperature and density can be easily determined. Our experimental data also show that as the argon gas pressure is varied from 0.1 Torr to 2 Torr, the electron temperature decreased from 2eV to 0.75ev, while the electron density increased from 7.5×10^7 cm^{-3} to 3.2×10^8 cm^{-3}.

The contribution of the ion currents from the ionization is mainly determined by the ionization potential and the neutral density n_n of the plasma as was expected. When the temperature of the wire (T_w) increases or the bias voltage (V_b) increases either positively or negatively with respect to the plasma potential, the ionization current will increase. Based on these observations, when measuring the plasma potential using the inflection point method, one should make sure to bias the probe voltage close to the region where the inflection occurs. This is to minimize the heating time and to avoid the excessive current due to the excessive ionization near the wire. The following steps are suggested to measure the plasma potential in high pressure plasma using the inflection point method :

1) Slowly increase the DC heating voltage until the emissive wire starts to glow white.

2) Sweep the probe bias from wider range (from -100V to +100V) in order to make sure that all of the ionization features are included.

3) Plot the I-V curve and look for the two bias voltage where the current begins to deviate from the ion and electron saturation current (see points B and G in Fig. 5). Subtract the ionization energy ε_ι of the gas from the upper voltage and add ε_ι to the lower voltage to get approximate value for lower plasma potential V_{PL} and high plasma potential V_{PH}

4) Sweep the probe with a shorter range bias voltage, for example from (V_{PL} - 20V) to (V_{PH} + 20V). This reduces the wire heating time and protects the circuits from measuring unnecessarily large current.

5) If the inflection point in the I-V curve is not apparent at V_{PL} and V_{PH}, increase the DC heating voltage of the emissive wire by small increments until the inflection point appears in the I-V curve.

6) Take the derivative of the current with respect to the bias voltage to look for the two peaks of the fluctuating plasma potentials V_{PL} and V_{PH}.

7) Decrease the emissive wire temperature by steps of 0.01V until the two peaks in step 6 are not detectable. This step is to insure finding the plasma potential at the limits of zero emission.

8) Calculate the time averaged plasma potential From V_{PL} and V_{PH} .

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APPENDIX: SOURCE CODE

(1) Plasma I-V curve characteristic detection program

/**

Plasma I-V curve characteristic detection program

This program uses computerBoard, Inc. interface card to detect the current and bias voltage of the Langmuir probe and emissive probe traces. A KEPCO Bipolar Operational Power Supply Amplifier is used to amplify the D/A chain 0 sweep voltage(-5V,+5V). A/D chain 0 is used to monitor the sweep bias voltage of the probe(-100, +1000)>. A/D chain 1 is used to collect the current measurement from the sample resistor. The current signal has been low-pass filtered. An isolation amplifier and output buffer are connected to D/A chain 1 for providing a floating emission filament voltage. Emission current is controlled by program at D/A chain 1.

The collected data are stored in the specific output file.

**/

```
/* Include files */
#include <stdio.h>
#include <conio.h>
#include <dos.h>
#include <ctype.h>
#include "cb.h"
#include "stdlib.h"
#define TRUE    1
#define FALSE   0

/* Prototypes */
void ClearScreen (void);
```

```
void GetCursor (int *x, int *y);
void MoveCursor (int x, int y);
float ADcollect1 (int Chan, float *axis);
void main ()
   {
   /* Variable Declarations */
   int ch,inc=1000;
   int Row, Col;
   int BoardNum = 0;
   int ULStat = 0;
   int Gain = BIP5VOLTS;
   int Chan, ExitFlag;
   int i,j;
   unsigned DataValue;
   float EngUnits,EngUnits1,EngUnits2,intervals;
   float I, V, axis,calibration=21;
   /* Initiate error handling
         Parameters:
            PRINTALL :all warnings and errors encountered will be printed
            STOPALL  :if any error is encountered, the program will stop */
   ULStat = cbErrHandling (PRINTALL, STOPALL);

  /* set up the display screen */
   ClearScreen();

   GetCursor (&Col, &Row);

   ExitFlag = FALSE;

   while (!ExitFlag)
   {
               FILE *outfile;               /*  output file */
               char filename[20];
               printf("\n Please enter the output file name :\n");
               scanf("%s",filename);
               outfile=fopen(filename,"w");
        Chan = 1;
        printf ("Enter a voltage for filament ");
        scanf ("%f", &EngUnits);
        ULStat = cbFromEngUnits(BoardNum, Gain, EngUnits, &DataValue);
        ULStat = cbAOut (BoardNum, Chan, Gain, DataValue);
        printf ("\n  %.2f volts has been sent to D/A 0.\n\n", EngUnits);
        MoveCursor (1, 20);
        printf ("\n");
```

```
        Chan = 0;
         EngUnits1=7;
         EngUnits2=-3;
          intervals=(EngUnits2-EngUnits1)/inc;
            for (i=0;i<=inc;i++)
                {
                 EngUnits=EngUnits1+i*intervals;
        ULStat = cbFromEngUnits(BoardNum, Gain, EngUnits, &DataValue);
        ULStat = cbAOut (BoardNum, Chan, Gain, DataValue);
        ADcollect1 (0, &axis);
        V=axis*calibration;
        ADcollect1 (1, &axis);
        I=-axis/2;
    printf("\n I= %.3f\tV=%.3f\tD/A Sweeep (V)=%.3f\n", I,V,EngUnits);
    fprintf(outfile,"%f\t%f\n",V,I);
                }
    printf("\n\n");
          EngUnits=7;
    ULStat = cbFromEngUnits(BoardNum, Gain, EngUnits, &DataValue);
    ULStat = cbAOut (BoardNum, Chan, Gain, DataValue);
    fclose(outfile);
    Chan  = 1;
           EngUnits=0;
    ULStat = cbFromEngUnits(BoardNum, Gain, EngUnits, &DataValue);
    ULStat = cbAOut (BoardNum, Chan, Gain, DataValue);

    printf ("\n Press Q to quit , any other key to continue:\n ");
              while (!kbhit()){ }
              ch=getch();
              if (ch=='q' || ch=='Q')
                     ExitFlag=TRUE;
        }
   printf ("\n");

 }
/*****************************************************************/

float ADcollect1 (int Chan, float *axis)
   {
   /* Variable Declarations */
   int Row,Col;
   int Row2,Col2;
   int BoardNum = 0;
   int ULStat = 0;
```

```
    int Gain = BIP5VOLTS;
    unsigned DataValue = 0;
          float EngUnits;

    /* Initiate error handling
      Parameters:
            PRINTALL :all warnings and errors encountered will be printed
            STOPALL  :if any error is encountered, the program will stop */

    ULStat = cbErrHandling (PRINTALL, STOPALL);
    /* get the A/D channel to sample */
          /*Parameters:
             BoardNum    :number used by CB.CFG to describe this board
             Chan        :input channel number
             Gain        :gain for the board in BoardNum
             DataValue   :value collected from Chan */

          ULStat = cbAIn (BoardNum, Chan, Gain, &DataValue);
          ULStat = cbToEngUnits (BoardNum, Chan, DataValue, &EngUnits);
          *axis = EngUnits;
          return ;
    }

/*****************************************************************/

#define BIOS_VIDEO   0x10

void
ClearScreen (void)
{
    union REGS InRegs,OutRegs;

    InRegs.h.ah = 0;
    InRegs.h.al = 2;
    int86 (BIOS_VIDEO, &InRegs, &OutRegs);
    return;
}

/*****************************************************************/
void
MoveCursor (int x, int y)
{
    union REGS InRegs,OutRegs;
```

```
  InRegs.h.ah = 2;
  InRegs.h.dl = (char) x;
  InRegs.h.dh = (char) y;
  InRegs.h.bh = 0;
  int86 (BIOS_VIDEO, &InRegs, &OutRegs);
  return;
}


/******************************************************************/

void
GetCursor (int *x, int *y)
{
  union REGS InRegs,OutRegs;

  InRegs.h.ah = 3;
  InRegs.h.bh = 0;
  int86 (BIOS_VIDEO, &InRegs, &OutRegs);
  *x = OutRegs.h.dl;
  *y = OutRegs.h.dh;
  return;
}
```

(2) Processing I-V curve program

```
/***************************************************************************

process I-V curve

This program takes a I-V curve file and smoothes the curve by averaging and
smoothing data, then I-V curve is subtracted by the load line. The average slope in
the entered voltage (x-axis) range and the I(0) value corresponds to the closest value
to v==0 are also calculated prior. Then puts the results in an output file.
This program also calculates the Te and De based on the given bias voltage range
of I-V curve.
***************************************************************************/

#include <stdio.h>
#include <math.h>
void main()
    {
    static float  ii[1000],vv[1000], avg_ii[1000],avg_vv[1000];
    float  vt,it,si,v_min,v_max,slope_value, Te, De;
    float slope=0, sum=0,Tsum=0,isum=0,ii_0,vv_0=0.3,sii=0,crii=0;
    int   j,k,c,ss=0,m=0, let=0,exit=0;
    int   N;  /* number of times to average the data */
    int  NP;  /* number of points*/
    char inname[20],outname[20];
    FILE *inputfile;
    FILE *outputfile;


    printf("\nDo you want to process I-V curves...(Y/y) ???? ");
    c=getchar();
    if (c=='Y'||c=='y')
      {
   /* averaging  the load_line file */

      printf("\nPlease enter the input loadfile name:\n");
     scanf("%s",inname);
     /* printf("\nHow many points do you want to average the line"); */
```

```
/* scanf("%d",&NP);*/
printf("\nHow many times do you want to average the line");
printf("\nRecommend 100 for loadline data====>");
scanf("%d",&N); /* how many times to average the date */
 inputfile=fopen(inname,"r");
 NP=1000;
for (k=0;k<NP;k++)
 {
  fscanf(inputfile,"%f %f\n",&vv[k],&ii[k]);
  }
for (j=0; j<N; j++)
 {

  for (k=0; k<(NP);k++ )
   {

   avg_vv[k]=(vv[k]+vv[k+1])/2;
     avg_ii[k]=(ii[k]+ii[k+1])/2;

     vv[k]=avg_vv[k];
     ii[k]=avg_ii[k];

      }

  printf ("\naverage time = %d\n", j+1);
  }


for (m=351; m<=750; m++)
   {
     slope_value= (ii[m]-ii[350])/(vv[m]-vv[350]);
     sum=sum+slope_value;
      if (fabs(vv[m])<vv_0)
        {
        /* vv_0=abs(vv[m]); */
         crii=ii[m];

         sii=crii+sii;

         ss=ss+1;
        }

      }
slope=sum/400.0;
```

```
printf ("\nThe slope =%f",slope);
ii_0=(sii/ss);
 printf ("\nThe shift =%f",ii_0);
fclose (inputfile);
printf("\nThen do you want to substract the loadline ...(Y/y) ???? ");
fflush (stdin);
c=getchar();
if (c=='Y'||c=='y')
      {
 /* substract the load_line  */
  while(!exit)
     {
         printf("\nPlease enter the input file name:\n");
           scanf("%s",inname);
           printf("\nPlease enter the output file name:\n");
           scanf("%s",outname);
          /* printf("\nHow many points do you want to average the line"); */
           /*scanf("%d",&NP);*/
           printf("\nHow many times do you want to average the line");
           printf("\nRecommend 100 for actual  data====>");
           scanf("%d",&N); /* how many times to average the date */

         inputfile=fopen(inname,"r");
           NP=1000;
          for (k=0;k<NP;k++)
          {
            fscanf(inputfile,"%f %f\n",&vv[k],&ii[k]);
            /* printf ("\nthe date is%f %f",vv[k],ii[k]);  */
             }
            for (j=0; j<N; j++)
              {

                  for (k=0; k<(NP);k++)
              {

                    avg_vv[k]=(vv[k]+vv[k+1])/2;
                    avg_ii[k]=(ii[k]+ii[k+1])/2;

                    vv[k]=avg_vv[k];
                    ii[k]=avg_ii[k];
                    }
                  NP=NP-1;
                    printf ("\naverage time = %d\n", j+1);
```

```
              }

           outputfile=fopen(outname,"w");
          for (k=0;k<(NP); k++)
          {
           ii[k]=ii[k]-(vv[k]*slope+ii_0);

           fprintf(outputfile,"%f\t%f\n",vv[k],ii[k]);
        }

     fclose(inputfile);
     fclose(outputfile);
      printf("\nDO you want to  to substract the data again 'Y/y' or 'n/N':");
       fflush(stdin);
       c=getchar();
       if (c=='N'||c=='n')
       exit=1;
               }

         }
        }

/* CAlculate Te & De */
printf("\nDo you want to calculate the Te & De (y/Y): ");
fflush(stdin);
c=getchar();
if(c=='Y'||c=='y')
 {
 printf("\nplease enter the file for Te measurement: ");
  scanf("%s",inname);
  inputfile=fopen(inname,"r");
  printf("\nEnter Te output file name\n");
  scanf("%s",outname);
 outputfile=fopen(outname,"w");
 printf("\nEnter the voltage range for Te measurement");
 printf("\nVmin=");
  scanf("%f",&v_min);
  printf("\nVmax=");
  scanf("%f",&v_max);
 m=0;
  NP=900;
 fprintf(outputfile,"\n\n %s",outname);
 for (k=0;k<(NP-1);k++)
  {
```

```
fscanf(inputfile,"%f\t%f\n",&vv[k],&ii[k]);

 if ((vv[k] >= v_min && vv[k] <= v_max))
   {

       m++;
      vt=vv[k];
      it=ii[k];
    Te=(vv[k-1]-vt)/(log(ii[k-1])-log(it));
       printf ("\n the Te is%f\n",Te );
       Tsum=Tsum+Te;
     fprintf(outputfile,"\nm=%d   Te=%2.4f  ii=%2.4f vv=%2.4f",
               m,Te,ii[k],vv[k]);


    printf ("\n the it vt are%f %f\n",it, vt );
     }
     }

    for (k=1;k<(NP-1);k++)
   {
      if (fabs(ii[k]-ii[k-1])<0.00004 &&  ii[k]<0)
      {
       let=let++;
       printf("\n the number is %d", let);
       isum=isum +ii[k];
      }
       else if (let>10)
         {
          printf("\n  The total times are %d", let);
          si=isum/let;
          De =(3.17e10*(fabs(si)))/sqrt(Te);
          NP=0;
         }
        else
         {
           isum=ii[k];
          let=0;
          }

    }
  /* printf("\nThe average Te between (%f-%f volt)==== %f
",v_min,v_max,sum/m); */
    printf("\nThe ion saturated current 1s === %f  ma  ",si);
```

```
        printf("\nThe average Te between (%f-%f volt)==== %f
",v_min,v_max,Tsum/m);
        printf("\nThe density is  %e ",De);
           fprintf(outputfile,"\nThe average Te between (%f-%f volt)==== %f
                                        ",v_min,v_max,Tsum/m);
        fprintf(outputfile,"\nThe density is=== %e",De);
        fclose(inputfile);
        fclose(outputfile);
             }
             printf("\n you have nice day !") ;
              }
```

APPROVED

Signed: Noah Hershkowitz

Noah Hershkowitz

Title: Professor of Nuclear Engineering and Engineering Physics

Date: August 20, 1996