Use of Langmuir Probes in High Density Plasmas

Francis F. Chen and John D. Evans

*Electrical Engineering Department, UCLA*

LTP-009

October, 2000

Electrical Engineering Department
Los Angeles, California 90095-1594
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Francis F. Chen* and John D. Evans**
University of California, Los Angeles, CA, USA

In this paper, existing calculations of saturation ion currents $I_i$ to Langmuir probes at potential $V_p$ are digitized and parametrized so that $I_i - V_p$ curves for given plasma density $n$, electron temperature $T_e$, and space potential $V_s$ can be reproduced in dimensional units rapidly on personal computers. Secondly, an iteration technique is used to separate the ion and electron currents in their overlap region near the floating potential. Probe measurements in an inductively coupled plasma (ICP) of the type used in semiconductor etching, were made in argon at various densities, pressures, RF powers, and probe radii $R_p$; and in one series $n$ was measured also by microwave interferometry. Results show that the collisionless theories do not agree at large values of the parameter $\xi \equiv R_p/\lambda_D$ ($\lambda_D =$ Debye length) and given values of $n$ bracketing the real value. The discrepancy is thought to be due to charge-exchange collisions in the presheath.

The main theories of ion collection are (a) the original orbital motion limited (OML) theory of Langmuir, the Allen-Boyd-Reynolds (ABR) theory [1], and the Bernstein-Rabinowitz theory [2] as extended to Maxwellian ions by Laframboise [3] (BRL). OML accounts for ion angular momentum but neglects the formation of thin sheaths. ABR includes sheaths but neglects orbiting. BRL accounts for both, but computed $I_i - V_p$ curves exist only for a few values of $\xi$ and are hard to reproduce. Furthermore, the curves are in dimensionless units which depend on the values of $n$, $T_e$, and $V_s$ that one wants to determine. These curves can be generated from the function

$$\frac{1}{t^4} = \frac{1}{\left(A\eta^b\right)^4} + \frac{1}{\left(C\eta^D\right)^4}, \quad \text{where} \quad \eta \equiv -\frac{e(V_p - V_s)}{K T_e}, \quad i = \frac{I_i}{enA_p\left(\frac{K T_e}{2\pi M}\right)}^{1/2}, \quad (1)$$

and the parameters $ABCD$ are functions of $\xi$. These functions are then further parametrized by fitting them to the following forms:

$$A = a + \frac{1}{b \xi_c^e} \exp(-d \xi^{-f}); \quad B, D = a + b \xi^{-c} \exp(-d \xi^{-f}); \quad C = a + b \xi^{-c}, \quad (2)$$

where different coefficients $abcdef$ apply to each parameter $ABCD$, as given in Table 1. These coefficients can reproduce the Laframboise curves to within 5%.

To separate the ion and electron currents, first guess the values of $n$, $T_e$, and $V_s$ and compute the theoretical ion curve using Eqs. (1) and (2). Then make a least-squares fit with the data by varying $n$ and $T_e$. Fig. 1 is an example of such an $I_i^2 - V$ plot. In general, the data
Table 1

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.12</td>
<td>0.0034</td>
<td>6.87</td>
<td>0.145</td>
</tr>
<tr>
<td>B</td>
<td>0.50</td>
<td>0.008</td>
<td>1.50</td>
<td>0.180</td>
</tr>
<tr>
<td>C</td>
<td>1.07</td>
<td>0.95</td>
<td>1.01</td>
<td>—</td>
</tr>
<tr>
<td>D</td>
<td>0.05</td>
<td>1.54</td>
<td>0.30</td>
<td>1.135</td>
</tr>
</tbody>
</table>

Fig. 1. Saturation ion current measured in a 2-MHz ICP at 200W in 20 mTorr of A, with a probe 0.15 mm in diam and 1 cm long. The lower curve is theoretical, computed from BRL for $T_i = 0$.

will follow a linear $I_i^2 - V$ relation more closely than the BRL theory. Using this value of $n$, one can then plot the electron current semilogarithmically, assuming a Maxwellian:

$$I_e = neA_p(KT_e/2\pi m)^{1/2} \exp[e(V_p - V_s^e)/KT_e],$$  

where $V_s^e$ is, unfortunately, different from the value of $V_s$ used to fit the ions. This straight line is shown in Fig. 2 together with the raw data and $I_e$ with the theoretical ion current subtracted. It is seen that the modified data follow a straighter line. The values of $T_e$ and $V_s^e$
are then adjusted for the best fit. Using the new value of $T_e$, the ion curve can be recomputed
and $n$ readjusted. If the modified $I_e$ is then subtracted from the ion data, the following $I_i-V$ curve results (Fig. 3):

![Graph showing fit of $I_i-V$ curve after iteration.](image)

The points at the right beyond $V_s$ appear because different values for $V_s$ had to be used to fit $I_i$ and $I_e$. This is an unresolved problem. The theory for $I_i$ near $V_s$ is subject to uncertainty, and the value of $V_s$ is sensitive to the curvature there. This points out the danger in computing the electron energy distribution function from the $I-V$ curve near the floating potential.

Since the ABR theory yields $I_i-V$ curve closer in shape to the data, this theory was also double-parametrized in a similar manner, using the computations of ABR theory by Chen [4] for cylindrical probes. The OML theory has the following simple form for $T_i = 0$:

$$I \to \frac{I_e}{eV_s} \to \frac{\sqrt{2} A_p n e}{\pi} \left( \frac{|eV_p|}{M} \right)^{1/2}. \quad (4)$$

The software for the ESPion® probe of Hiden Analytical, Ltd. uses OML theory. We have analyzed a large number of $I-V$ curves using these three theories. Examples for four values of $\xi$ are shown in Fig. 4. The resulting values of $T_e$ are insensitive to the theory used, but the $n$ values differ widely. OML fits the shape of the curves best, but it should not be valid for $\xi > 3$ and requires an unreasonably high value of $V_s$. The ABR theory gives too low a value of $n$, and the BRL theory shows more saturation than is observed.

The disagreement in densities found from different theories increases with $\xi$, as shown in Fig. 5, and reaches factors of 3 or more. In Fig. 6, BRL and ABR densities are compared with microwave interferometry measurements for increasing RF power. It is seen that ABR yields too low a density, as expected since orbiting is neglected and therefore too high an $I_i$ is predicted. BRL yields too high a density. We believe that this is because orbiting to over-emphasized. In partially ionized plasmas, incoming ions can lose their
angular momentum and be drawn in radially in their final trajectory. Curiously, the geometric mean of the BRL and ABR densities seems to agree with the microwave results.

\[
\begin{align*}
\xi = 1.1 & \quad \xi = 3.1 & \quad \xi = 4.6 & \quad \xi = 9.1
\end{align*}
\]

Fig. 4. Values of \( T_e \) (points) and \( n \) (bars) obtained from different theories.

Fig. 5. Ratio of \( n \) obtained from BRL (upper curve) and ABR (lower curve) theories, normalized to that from OML theory. The points (*) lying off the BRL curve result if the wrong value of \( R_p \) is used.

Fig. 6. Comparison of BRL (O) and ABR ( ) densities with microwave measurements (Ø). The (*) points are the geometric mean between the BRL and ABR densities.

Until a simple collisional theory is available for such plasmas, it is best to use small \( R_p \) at low \( n \), so that OML can be used, and large \( R_p \) at high \( n \), so that orbiting does not occur.

This work was supported by Applied Materials, Inc., Hiden Analytical, Ltd., and the University of California SMART program.

* ffchen@ee.ucla.edu  ** jdevans@ucla.edu