COMPARISON OF COMMERCIAL PLASMA PROBE SYSTEMS

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Introduction

Today, plasma simulation codes are practically the main tool in studying plasma electrodynamics, plasma transport and plasma kinetics in industrial plasma sources. These codes applied to complicated processing gas mixture are sometime missing many cross sections for variety of plasma-chemical reactions.

They also are missing effects of nonlocal and nonlinear plasma electrodynamics that has been proved important and even dominant in rf plasmas at low gas pressure.

In such situation, a reliable measurement of the plasma parameters would give a valuable experimental data for understanding variety of electrodynamics, transport and kinetic process in such plasmas and for validation of existing theoretical models and numerical codes.
Probe diagnostics is ideally suited for measurement in plasma processing reactors (providing it done professionally)

“There is no plasma diagnostics method other than probe diagnostics where the danger of incorrect measurements and erroneous interpretation of results are so great.”


It was true then, it is even more true today, when plasmas are more complicated and the measurements are more sophisticated. Still, technical limitations of many contemporary commercial probe systems may lead to significant errors
Three levels of probe diagnostics

Plasma parameters are inferred from:

1. **Ion part of the probe I/V characteristic $I_i$ (double and triple probes).**
   Is notoriously inaccurate (up to an order of magnitude error) due to many unrealistic assumptions in existing $I_i(V)$ theories

2. **Electron part of the probe I/V** (classic Langmuir method). Assumes Maxwellian EEDF. Uncertainty in plasma potential and arbitrariness in ion current approximation lead to significant error in plasma density calculation and wrong judgment about fast electrons

3. **Differentiation of the probe characteristic** Generates the EEDF as the output with the plasma parameters calculated as corresponding integrals of the measured EEDF

Since EEDFs in gas discharge plasmas are never Maxwellian (at both, $\varepsilon < \varepsilon^*$ and $\varepsilon > \varepsilon^*$), EEDF measurement is the only reliable probe diagnostics adequate to contemporary level of gas discharge science
Ion part of the probe I/V

\[ T_e = \frac{d(I - I_i)}{I_i dV} \] @ \( V = V_f \)

N is found from one of theories: Radial, or Orbital motion, or Laframboise. Which one to use ???

Unrealistic assumptions for \( I_i(V) \):

- Maxwellian EEDF,
- No ion collisions \( (\lambda_i << \lambda_e) \)
- One-dimensional probe sheath
- Uncertainty in \( V_s \)
- No ambipolar flow \( (v_s \geq v_{amb} > v_{Ti}) \)
- The ion temperature is unknown
- Inferred \( T_e \) is affected by fast electrons of the EEDF, while ion current \( (N_i) \) by slow electrons

\[ V_s - V_f = \left( \frac{1}{2} \right) T_e \ln(M/2\pi m) \]

is only valid for Maxwellian EEDF and \( \lambda_D << a_p \)

Numerous studies showed that plasma parameters found from the ion part of the probe characteristic can be in error, up to order of magnitude! ↓ ↓ ↓ ↓ ↓ ↓

Godyak et al, J. Appl. Phys. 73 3657, 1993
Electron part of the probe I/V
(Classical Langmuir technique)

Main problems:

- Assumption of Maxwellian EEDF
- Uncertainty in plasma potential $V_s$
- Arbitrariness in the ion current approximation

Because of exponential dependence of the electron saturation current, $I_{e0} \propto \exp(V/T_e)$, a moderate uncertainty in $V_s$ can lead to great error in $I_{e0}$, and thus, in the plasma density $N \propto I_{e0}$.
Comparison of the three probe methods

From Ion part: $T_e = 1.4 \text{ eV}, \ N = 9.6 \cdot 10^9 \text{ cm}^{-3}$

From Langmuir: $T_e = 1.37 \text{ eV}, \ N = 4.5 \cdot 10^9 \text{ cm}^{-3}$

From EEDF: $T_e = 3.4 \text{ eV}, \ N = 2.9 \cdot 10^9 \text{ cm}^{-3}$

2.5 times $1.5$ and $3.3$ times

Sudit and Woods have shown an error (up to order of magnitude) for $N$ found from $I_i$

Godyak et al, J. Appl. Phys. 73, 3657 (1993)

Probe I/V differentiation

Druyvestein (1931) showed that $\frac{d^2I_e}{dv^2} \propto \text{EEPF, } f(\varepsilon)$, while $\text{EEDF, } F(\varepsilon) \propto \varepsilon^{1/2}f(\varepsilon)$

- Applicable to arbitrary isotropic $f(\varepsilon)$
- Accurate $V_s$ measurement
- Plasma parameters, rate of e-collisional processes and transport coefficients can be readily found as integrals of $f(\varepsilon)$
- Since, in most cases the low temperature plasma is non-Maxwellian, the only reliable probe diagnostics for laboratory and processing plasmas is EEDF measurement

Electron probability function (EEPF) measured in Ar CCP @ 13.56 MHz, 30 and 300 mTorr


Popular commercial probe systems on the market

ALP, Impedans (Ireland)  
“\textit{The Langmuir Probe™ is by far the best commercial Langmuir Probe on the market, ...}”; “\textit{...is the fastest* and most reliable Langmuir probe in the world (time resolution 12.5 ns*)}”.

ESPion, Hiden (UK)  
“\textit{ESPion has the highest blocking impedance of any commercially available unit-4.25 M\text{\small Ohm} at 13.56 MHz*...}”  
“\textit{ESPION has more than x10* the resolution of other commercial Langmuir probes.}”

MFPA, Plasma Sensors (USA)  
“\textit{Able to measure and display the true EEDF in the real time}”; “\textit{...unique state-of-the-art features unavailable in any other commercial products}”.

•  *Highlighted features and numbers may mislead users (acquisition rate does not define the time response of the probe system, inductive impedance of the probe filter does not define RF rejection ratio)
•  Because of poorly defined parameters of probe systems it is hard to compare them based on specifications alone
•  Indeed, ALP and ESPion have similar characteristics, and both differs from MFPA’s
•  Superior performance of a particular probe system can be proven only by comparing the data quality obtained by similar instruments.
EEDF measurement comparison 1

Impedance ALP

Plasma Sensors VGPS

Ar ICP, 2.2 mTorr

Low energy peak in EEDF is typical in a low pressure ICP dominated by anomalous skin effect

Ar ICP, 0.3; 1 and 10 mTorr

Gahan et al, PSST 17, 035026 (2008)

Godyak et al, PSST 11, 525 (2002)
EEDF measurement comparison 2
(Dynamic and energy range and resolution)

PEGASES. Ar 10 mTorr, 100 W.
Ecole Polytechnique, France

ICP with ferrite core. Ar 1.2 mTorr, 40 W
Tsinghua University, China
EEDF measurements in a commercial ICP reactor

Comparison of EEPF measured with different commercial probe stations, Espion of Hiden and VGPS of Plasma Sensors

At maximal discharge power of 2 kW, \( N \approx 1 \cdot 10^{12} \text{ cm}^{-3} \), thus the EEPF @ \( \varepsilon < \varepsilon^* \) has to be a Maxwellian one

“Druyvesteynization” effect is found in many publications of EEDF measurements made with home-made and commercial probe systems

V. Godyak et al, GEC 2009, Saratoga Springs, NY, USA
Measuring of EEDF in reactors with processing gases

Wide specter and large amplitude of rf plasma potential, low-frequency noise, high rate of probe contamination and bad plasma contact to the grounded chamber are the major problems making difficult probe diagnostics there.

Measurement in the same ICP reactor. Oxygen 10 mTorr
MFPA Display
Examples of EEDF in plasma reactors measured with Plasma Sensors instrument

Ar, O₂, HBr, HBr+O₂

EEPf in commercial two-inductor ICP in different processing mixtures at 15 mTorr.
Mattson Technology

Ar+ SiH₄

EEPf in ECR array reactor, Ar/SiF₄ at 10 mTorr with microcrystalline silicon deposition.
Ecole Polytechnique

Ar, Ar + H₂

EEPf measured in ICP reactor, H₂/CF₄ at 30 mTorr with a polymer layer deposition.
University of Maryland
Time resolved EEDF in Ar positive column with moving striations

Ar, 10 mTorr, 3 A, 65 cm from the cathode

\[ F \approx 15 \text{ kHz}, \quad \Delta V_p \approx 8 \text{ V}, \quad \frac{n_{\text{max}}}{n_{\text{min}}} \approx 4, \quad \frac{T_{e\text{max}}}{T_{e\text{min}}} \approx 2 \]

Period 65 µS  Time resolution 2.5 µS

Time averaged EEPF in moving and in standing striations

Probe floating potential \( V_f(t) \)
Conclusions

• EEDF measurement is only reliable probe diagnostics providing accurate plasma parameters, rates of plasma-chemical processes and transport coefficients.

• Design of EEDF measurement arrangement requires professional skill in analog and digital electronics and deep knowledge of gas discharge physics.

• Majority of commercial probe instruments unable to accurately measure of EEDF having too low both, energy resolution and dynamic range of EEDF measurement.


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