Langmuir probe measurements in an expanding magnetized plasma

Citation for published version (APA):
Brussaard, G. J. H., Steen, van der, M., Carrere, M. H. M., Timmermans, E. A. H., Sanden, van de, M. C. M., Mullen, van der, J. J. A. M., & Schram, D. C. (1997). Langmuir probe measurements in an expanding magnetized plasma. In P. Fauchais (Ed.), *Progress in Plasma Processing of Materials 1997 : Proceedings of the International Thermal Plasma Processes Conference, 4th, Athens, July 15-18, 1996* (pp. 255-261). Begell House Inc..

Document status and date:
Published: 01/01/1997

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 04. Oct. 2023

LANGMUIR PROBE MEASUREMENTS IN AN EXPANDING MAGNETIZED PLASMA.

G.J.H. Brussaard, M. van der Steen, M. Carrère, E.A. Timmermans,
M.C.M. van de Sanden, J.A.M. van der Mullen, and D.C. Schram

*Department of Physics, Eindhoven University of Technology, P.O.Box 513, 5600 MB
Eindhoven, The Netherlands*

Abstract:
Langmuir probe measurements are performed in magnetized expanding plasmas of different compositions. Under the assumption that a function fitted to results in argon is valid in other plasmas, it is possible to investigate the influence of the magnetic field in nitrogen and hydrogen plasmas. It is found that the electron density in nitrogen can be increased by a factor of 10 by the application of a magnetic field of 4.5 mT. In hydrogen the density can be increased by a factor of 100 by a magnetic field of 20 mT. The dominant ionic species in the magnetized nitrogen and hydrogen plasmas is found to be the atomic ion (N^+ and H^+, respectively).

1. INTRODUCTION

Expanding plasmas have become increasingly interesting for application in a wide variety of technologies. As a hydrogen particle source they are used for surface modification, passivation and plasma cleaning of iron archaeological artifacts [1]. The rgon hydrogen plasma serves as a precursor for deposition plasmas that are used for fast deposition of amorphous hydrogenated silicon (a-Si:H), amorphous carbon (a-C:H), diamond and silicon nitride (SiN_x) layers [2, 3, 4]. Nitrogen plasmas are used to ealize wear resistant and anticorrosive layers such as titanium nitride (TiN) and is of fundamental interest in the study of N_2/O_2 mixtures for the understanding of reentry problems with spacecraft.

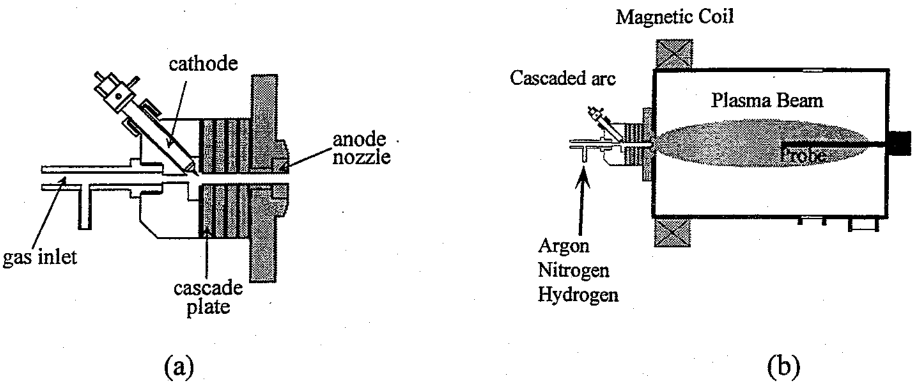

figure 1: The cascaded arc (a) and expanding plasma (b)

In order to optimize these applications it is necessary to investigate the influence of different plasma parameters on these processes. Two important plasma parameters are the ionization degree and the temperature of the plasma. To measure these parameters, the static Langmuir probe is one of the most widely used techniques.

2. EXPERIMENTS

Cascaded arc plasma

The plasma source used is the cascaded arc (figure 1(a)), with three cathodes, a stack of four isolated copper plates with a 4 mm bore and an anode nozzle. The current is set to 50 A in the experiments described here. The voltage drop depends on the gas flow rate and gas composition and ranges from 50-100 V. Details of the operation of the cascaded arc can be found in [5]. The gas is injected at the cathode side and is dissociated/ionized in the arc channel. The plasma is then allowed to expand supersonically into a low pressure chamber (figure 1(b)).

Table I: Overview of experimental conditions

Ar flow	0.3 and 1 slm
N_2 flow	1.4 slm
H_2 flow	2 slm
Arc current	50 A
Downstream:	
Chamber pressure	10-30 Pa
Magnetic field	0-18 mT
Electron density	10^{15} - 10^{18} m^{-3}
Electron temperature	0.1 - 1 eV

The ion density at larger distances from the nozzle can be increased by applying a magnetic field. For this purpose a coil around the nozzle provides a diverging magnetic field downstream parallel to the plasma flow with a maximum field strength of 40 mT. Some typical values for these plasmas are given in table I.

3. GENERAL PROBE THEORY

For the investigation of the electron temperature and density of the plasma a planar probe was constructed. The probe is a circular probe made out of tungsten. The probe radius is 2 mm and the edges of the probe are shielded off by a ceramic (Al_2O_3) tube.
The probe is immerged in the plasma at a distance of 25 cm from the nozzle for argon and nitrogen, and 16 cm for hydrogen. The normal to the probe surface is parallel to the flow and the applied magnetic field. The current collected by the probe is measured as a function of the applied potential relative to ground.

The Debye length in the plasma is very small (of the order of 10^{-5} m) compared to the probe diameter and the mean free path is of the order of the probe diameter, so a collisionless sheath may be assumed. The electron and ion temperatures are approximately equal, therefore the ion and electron saturation currents are given by [6]:

$$I_{s\,i,e} = -\frac{1}{4} \cdot n_{i,e\,0} \cdot \bar{v}_{i,e} \cdot q \cdot A_p \qquad (1)$$

with $n_{i,e0}$ the ion and electron density of the undisturbed plasma, $\bar{v}_{i,e}$ the mean velocity and q the charge of the particles. A Maxwellian velocity distribution is assumed so that $\bar{v}_{i,e} = \sqrt{\frac{8}{\pi}\frac{kT}{m_{i,e}}}$, with T the temperature, $m_{i,e}$ the mass of the particle and k Boltzmann's constant. The ratio between electron and ion saturation current becomes:

$$\frac{I_{se}}{I_{si}} = \sqrt{\frac{m_i}{m_e}} \qquad (2)$$

which is 270 for argon.

The application of a magnetic field reduces the mobility of electrons and consequently the electron current to the probe. For a planar, circular probe with the normal of its surface parallel to the magnetic field the electron saturation current becomes [7]:

$$I_{e\parallel} = I_0 \cdot \beta \tag{3}$$

with I_0 the undisturbed, random current given by eq.(1) and a reduction $\beta^*(B)$ due to the magnetic field of [8]:

$$\beta^* = \left(1 + \frac{\pi}{8}\frac{\ell}{\lambda}\left(1 + \left(\lambda/\rho_e\right)^2\right)^{1/2}\right)^{-1} \tag{4}$$

with r_p the probe radius and ρ_e the Larmor radius. The parameter ℓ is a fitting parameter. Results in argon [8] yield $\ell = 1.2 \pm 0.2$ mm. Using this value the difference between theory and measurements is less than 20%. The ratio of saturation currents becomes:

$$\frac{I_{se\parallel}}{I_{si}} = \sqrt{\frac{m_i}{m_e}} \cdot \beta^* \tag{5}$$

4. RESULTS

If it is assumed that the empirically derived equation (eq.(4)) and value for ℓ are also valid for gases other than argon it is possible to use the probe in the investigation of other, more complicated, magnetized plasmas.

A pure nitrogen plasma was created with a total flow of 1.4 slm at a pressure inside the vessel of 23 Pa. The electron densities vary between $0.7 \cdot 10^{17}$ m^{-3} at $B = 0$ and $5 \cdot 10^{17}$ m^{-3} at $B = 4.5$ mT. The measured ratio of saturation currents at different values of the magnetic field are shown in figure 2(a). Because nitrogen forms two possible ions (N^+ and N_2^+) the current ratio will be determined by the relative densities of these ions:

$$\frac{I_{se}}{I_{si}} = \sqrt{\frac{m_{N^+}\left(\dfrac{n_{N^+} + 2n_{N_2^+}}{n_i}\right)}{m_e}} \cdot \beta^* \tag{6}$$

with n_{N^+} and $n_{N_2^+}$ the N^+ and N_2^+ densities, and n_i the total ion density.

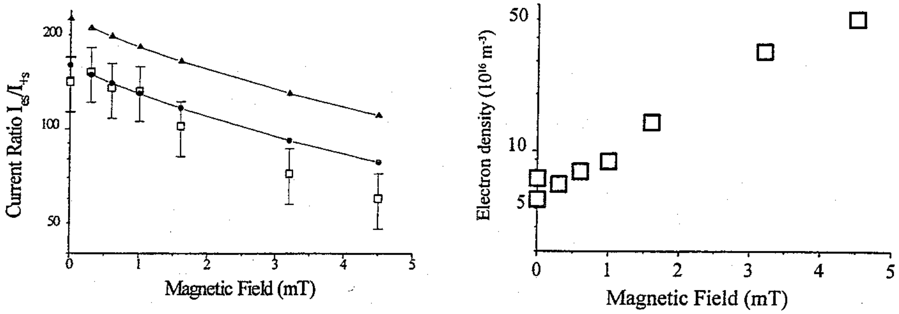

Figure 2: *Results from the nitrogen plasma with a total flow of 1.4 slm. The open symbols (□) are measured values. The solid symbols are results from calculations assuming that all ions are N^+ (●) and N_2^+ (▲) respectively.*

In figure 2(a) the calculated current ratios are given for two distinct cases: $n_{N^+}/n_i = 1$ and $n_{N^+}/n_i = 0$. It is clear that a best fit would yield $n_{N^+}/n_i = 1$. Taking into account the accuracy derived in the previous section it is possible to conclude that in this magnetized plasma the atomic ion N^+ is the dominant ionic species. This result is in agreement with mass spectrometry measurements performed by Dahiya et al.[9]. Because the dominant ionic species has been found, it is possible to calculate the ion (and electron) denisities from the (undisturbed) ion saturation current. The results are shown in figure 2(b)

In figure 3(a) the saturation current ratio in a pure hydrogen plasma, at a distance of 16 cm from the nozzle, at a flow rate of 2 slm and a chamber pressure of 23 Pa, is shown as a function of magnetic field. Because hydrogen is known to form many different ions [10] (H^+, H_2^+, H_3^+, etc.), the saturation current becomes:

$$\frac{I_{se}}{I_{si}} = \sqrt{\frac{m_{H^+} \cdot \sum_{p=1..} \frac{p \cdot n_{H_p^+}}{n_i}}{m_e}} \cdot \beta^* \tag{7}$$

with p the number of atoms in an ion and $n_{H_p^+}$ the density of the H_p^+ ion.

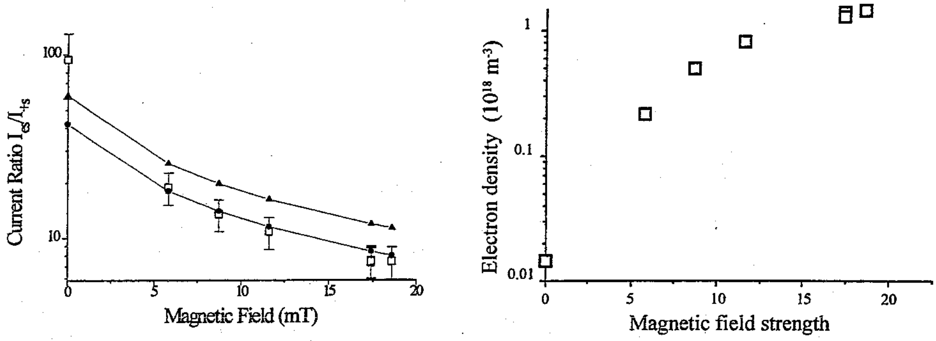

Figure 3: *Results from the hydrogen plasma with a total flow of 2 slm. The open symbols (□) are measured values. The solid symbols are results from calculations assuming that all ions are H^+ (●) and H_2^+ (▲) respectively.*

In figure 3(a) the calculated current ratios are given for $n_{H^+}/n_i = 1$ and $n_{H_2^+}/n_i = 1$.

From these calculations it is possible to conclude that in the magnetized hydrogen plasma the dominant ion is H^+. Again, the ion densities can now be calculated from the ion saturation currents. The results are shown in figure 3(b).

5. CONCLUSIONS

Under the assumption that an empirical formula to describe the electron saturation current in argon is also valid in plasmas with a different composition, it can be concluded that the dominant ion in the magnetized nitrogen and hydrogen plasmas is the atomic ion (N^+ and H^+, respectively). With this information it was possible to determine electron denisities in these magnetized plasmas.

Acknowledgments

The authors thank M.J.F. van de Sande, A.B.M. Hüsken and H. de Jong for their technical assistance. This work was supported by the Netherlands Technology Foundation (STW) and the Royal Netherlands Academy of Arts and Sciences (KNAW). This work is part of a collaborative effort between Wright Patterson Air Force Base and Eindhoven University of Technology and has been supported under the EOARD contract number SPC-95-4039.

REFERENCES

---

1 M.J. de Graaf, R.J. Severens, L.J. van IJzendoorn, F. Munnik, H.J.M. Meijers, H. Kars, M.C.M. van de Sanden and D.C. Schram, Surf. Coat. Tech. **74-75**, 351 (1995).
2 R.J. Severens, G.J.H. Brussaard, M.C.M. van de Sanden and D.C. Schram, Appl. Phys. Lett. **67** (4), 491 (1995).
3 A.J.M. Buuron, M.C.M. van de Sanden, W.J. van Ooij, R.M.A. Driessens, D.C. Schram, J. Appl. Phys. **78** (1), 528 (1995).
4 A.J.M. Buuron, J.J. Beulens, P. Groot, J. Bakker and D.C. Schram, Thin Solid Films **212** (1-2), 282 (1992).
5 R.F.G. Meulenbroeks, R.A.H. Engeln, M.N.A. Beurskens, R.M.J. Paffen, M.C.M. van de Sanden, J.A.M. van der Mullen and D.C. Schram, Plasma Sources Sci. Technol. **4**, 74 (1995).
6 H. Mott-Smith and I. Langmuir, Phys Rev. **28**, 727 (1926).
7 T. Dote, H. Amemiya and T. Ichimiya, Jpn. J. App. Phys. **3** (12), 789 (1964).
8 G.J.H. Brussaard, M. van der Steen, M. Carrère, M.C.M. van de Sanden and D.C. Schram, accepted for publication in Phys. Rev. E (1996).
9 R.P. Dahiya, M.J. de Graaf, R.J. Severens, H. Swelsen, M.C.M. van de Sanden and D.C. Schram, Phys. Plasmas **1** (6), 2086 (1994).
10 E. Graham, D.R. James, W.C. Keever, I.R. Gatland, D.L. Albritton and E.W. McDaniel, J. Chem. Phys. **59**, 999 (1990).