Development of a Probe System for Measuring the Plasma Parameters and the High-Energy Part of the Electron-Energy Distribution Function

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Abstract—A probe system has been developed on the basis of an external ADC/DAC module (ADC is the analog-to-digital converter and DAC is the digital-to-analog converter). Using this system, it is possible to determine all the main plasma parameters of continuous and pulsed gas discharges. A program for the Windows operating system has been developed in C++ to control the probe system. The probe system can be used for diagnostics of plasma devices and can be included in modern microplasma analyzers of gas mixtures.

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INTRODUCTION

Local diagnostics of nonequilibrium gas-discharge plasmas is the most important experimental stage of plasma physics, which provides a means for determining the plasma potential, as well as the electron concentration, temperature, and distribution function [1–11]. It helps to correctly understand the processes that occur in gas-discharge plasmas and predict the properties of developed plasma generators and plasma-based devices. A Langmuir probe, which is a small metal electrode immersed in plasma, is the simplest and most reliable tool for local plasma diagnostics [1–6]. The probe is connected to a power source that maintains both positive and negative potentials applied to it. By measuring the current delivered to the probe, we obtain the so-called probe characteristic that provides information on the plasma parameters [1–6].

It should be noted that the ideas of probe plasma diagnostics, which consist in measuring the high-energy part of the nonlocal distribution function in the plasma region of the negative glow discharge in a buffer noble gas with impurities, have also found application in the development of microplasma analyzers of gas mixtures [11–14].

There are a number of commercially produced probe systems, e.g., the MFPA system from Plasma Sensors [15, 16], the Impedans system [17] of the same-name company, or the Hiden ESPION system from Hiden Analytical Ltd [18]. These are able to measure probe characteristics in the real-time mode and to determine all the main plasma parameters from them. We note that the Impedans and ESPION systems are sensitive to noise while measuring the high-energy part of the electron energy distribution function (EEDF), which requires the manufacture of special filters and amplifiers for comprehensive diagnostics of the gas-discharge plasma [15, 19]. In addition, their extremely high cost and large sizes are the main disadvantages of all these systems, which rule out their use as components in microplasma gas analyzers [10–14].

In view of this, this work was aimed at developing a compact probe system capable of measuring the probe characteristics and determining the main plasma parameters and, in particular, the EEDF in continuous and pulsed gas discharges.

THE DESCRIPTION OF THE PROBE SYSTEM

The probe measurement system was developed on the basis of an external L-CARD E14-140M ADC/DAC module (ADC is the analog-to-digital converter, and DAC is the digital-to-analog converter). The main parameters of this module were as follows: the 14-bit ADC operated at a frequency of up to 200 kHz and had 16/32 switching channels and sub-bands of ±10, ±2.5, ±0.6, and ±0.15 V for asynchronous and synchronous data-acquisition modes, and the 16-bit DAC had two ±5 V channels with a current of up to ±10 mA and a frequency of up to 200 kHz for each channel. Continuous acquisition and readout of analog ADC–DAC data, asynchronous digital input

GENERAL EXPERIMENTAL TECHNIQUES

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of 16-bit data, and output of 16-bit data were provided. The block diagram of the probe system is shown in Fig. 1. The probe bias source used a battery power supply. Galvanic isolation was carried out using a high-linearity analog HCNR-200 optocoupler, to which the voltage was supplied from one of the DACs. The probe current was converted into the voltage using an operational amplifier and the sensitivity could be programmatically changed during measurements. The voltage was fed to the input of one of the ADC channels.

The signal accumulation method was used in the control program for operation in the stationary mode. The integration time was set in the control window for this purpose. All the probe characteristics measured during integration were averaged to obtain one resulting probe volt–ampere characteristic (VAC).

The ATmega 8535 microcontroller was used in the system for operation in the pulse mode. It set the period of a pulse discharge, the duration of the active phase, the opening time of the electronic switch, and the measurement time in the desired afterglow phase. All these parameters were set from a personal computer via E14-140M digital outputs.

The E14-140M module was connected to a personal computer via a USB port. The control program for the Windows operating system was written in C++ for this data-acquisition system. It was used to set the parameters of the probe system, display the VAC, as well as the first and second derivatives during measurements, and record results in a text file. The first and second derivatives were determined by numerical differentiation.

The developed program made it possible to determine all the main plasma parameters. As an example, Fig. 2 shows the window of the control program in the VAC measuring mode and the first and second derivatives in the plasma of a positive column of a glow discharge in helium in the afterglow mode. The figure displays the determination of the electron temperature by the linear segment of the logarithmic dependence for the first derivative of the probe current on the probe potential according to the formula [1–5]

\[ T_e = \frac{e \Delta U}{k \Delta (ln i')} \].  

(1)

If one measures the high-energy EEDF part in the afterglow plasma or in the stationary negative-glow plasma of a glow discharge in pure noble gases or in noble gases with impurities, narrow peaks (maxima) can be formed by electrons produced in Penning ionization reactions and second-kind shocks involving metastable noble-gas atoms [1, 10]:

\[ A + B^* \rightarrow A^+ + B + e(E_p), \]  

(2)

\[ e + B^* \rightarrow B + e(E_f), \]  

(3)
where $E_p$ and $E_f$ are the energies of the fast-electron production.

If fast electrons generated in these reactions do not have time to change their energy in electron−atom and electron−electron collisions and pass towards the walls in the free diffusion mode [20], then the number of fast electrons that can be determined by integrating the EEDF can be easily related to the concentration of metastable atoms. The characteristic time of free diffusion of electrons in the case of a cylindrical geometry of the discharge tube is determined by the expression

\[ \tau_{df}^{-1} = D_e \left( \frac{2\pi}{R} \right)^2 + \left( \frac{\pi}{L} \right)^2, \]

where $D_e$ is the diffusion coefficient, $R$ is the tube radius, and $L$ is the tube length. The concentration of metastable atoms can be estimated using the results of the integration of the kinetic equation for the isotropic EEDF part [1, 10]:

\[ S_e(0) = 0.78 k_{im} N_f(0) N_m(0) \tau_{df}, \]

where $N_f(0)$ and $N_m(0)$ are the concentrations of particles participating in the reaction at the center of the discharge tube, $S_e(0)$ is the concentration of fast electrons, and $k_{im}$ is the rate constant of this reaction. The EEDF can be experimentally determined using the Druyvesteyn formula, which is conveniently written in the form [1–4]

\[ f_e(e) = \frac{2\sqrt{2}}{S_e^2} \int \frac{m}{e} \frac{d^2i_e}{dU^2}, \]

In this expression, $i_e$ is the electron current delivered to the probe, $U$ is the probe potential relative to the plasma potential, $S$ is the probe area, and $f_e(e)$ is normalized to the electron concentration. Thus, by measuring the EEDF, it is possible to determine the concentrations of metastable atoms and electrons. The control program allows this calculation to be automatically performed during the experiment, which is illustrated in Fig. 3.

Figure 3 shows the measured peaks in the high-energy part of the EEDF in a glow discharge in helium at a pressure of 4.8 Torr and a discharge current of 8 mA. The calculated concentrations of metastable helium atoms and the electron concentrations are also shown in Fig. 3.

The probe VACs were measured using the developed probe system and the MFPA system from Plasma Sensors [14, 15]. Below, we present the results of the comparison of their second derivatives. Figure 4 shows the probe VACs and their second derivatives obtained using the numerical method and two probe systems in a glow discharge in helium with air impurities.

Peaks from fast electrons were recorded at the high-energy part of the EEDF in both cases. Thus, peaks are observed in the range of 19.8–20.0 eV, which corresponds to electrons produced in superelastic reactions:

\[ \text{He}(2^3 S) + e \rightarrow \text{He} + e \{ 19.82 \ \text{eV} \}, \]

\[ \text{He}(2^1 S) + e \rightarrow \text{He} + e \{ 20.61 \ \text{eV} \}. \]

In addition, peaks in the regions of 3.1, 4.2, and 6.2 eV are clearly discernible in both cases. They are associated with electrons produced in the reactions of Penning ionization of impurity molecules by metastable helium atoms [13]:

\[ \text{He}(2^3 S) + \text{N}_2 \rightarrow \text{He} + \text{N}_2(2^1 \Pi^+) + e \{ 3.1 \ \text{eV} \}, \]
It can be seen that the results practically coincide, thus indicating the reliability of the developed probe system.

CONCLUSIONS

A probe system has been developed and produced, with which it is possible to automatically measure all the main plasma parameters, concentrations of charged particles, and electron temperatures, as well as the EEDF. This probe system compares well in functionality to commercially produced analogs. In addition, the probe system is compact, which is important for designing miniature microplasma gas analytical systems based on it.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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REFERENCES
1. Demidov, V.I., Kolokolov, N.B., and Kudryavtsev, A.A., "Zondovye metody issledovaniya nizko-temperaturnoi plazmy" (Probe Methods for Researching Low-Temperature Plasma), Moscow: Energoatomizdat, 1996.
2. Ivanov, Yu.A., Lebedev, Yu.A., and Polak, L.S., "Mетоды контактной диагностики неравновесной плазмокимии" (Contact Diagnostics Methods for Non-Equilibrium Plasma Chemistry), Moscow: Nauka, 1981.
3. Kagan, Yu.M. and Perel’, V.I., "Uspekhi Fiz. Nauk," 1973, vol. 81, p. 409.
4. Chen, F.F., in "Plasma Diagnostic Techniques," Huddleston, R.H. and Leonard, S.L., Eds., New York: Academic, 1965.
5. Lebedev, Yu.A., "Vvedenie v zondovuyu diagnostiku plazmy ponizhennogo davleniya" (Introduction to Probe Diagnostic of Low-Pressure Plasma), Moscow: Moscow Engineering Physics Institute, 2003.
6. Chen, F.F., "Langmuir Probe Analysis for High Density Plasmas, LTP-006," Los Angeles, CA: Univ. of California, 2000.
7. Gorshunov, N.M. and Potanin, E.P., "Instrum. Exp. Tech.," 2018, vol. 61, no. 4, pp. 543–547. https://doi.org/10.1134/S0020441218040061
8. Kozhukhov, S.A., Ivanov, V.N., Shaposhnikov, A.N., Kotelnikov, D.V., Balugin, N.V., and Peremeshko, T.M., "Instrum. Exp. Tech.," 2017, vol. 60, no. 4, pp. 589–595. https://doi.org/10.1134/S0020441217030216
9. Yuan, C., Kudryavtsev, A.A., Saifutdinov, A.I., Sysoev, S.S., Yao, J., and Zhou, Zh., "Plasma Sources Sci. Technol.," 2019, vol. 28, no. 6, p. 067001. https://doi.org/10.1088/1361-6595/ab2401
10. Rudenko, K.V., Myakon’kikh, A.V., and Orlikovsky, A.A., "Russ. Microelectron.," 2007, vol. 36, no. 3, pp. 179–192. https://doi.org/10.1134/S1063739707030079
11. Kolokolov, N.B. and Blagoev, A.B., "Uspekhi Fiz. Nauk," 1993, vol. 163, p. 55. https://doi.org/10.3367/UFNr.0163.199303c.0055
12. Kudryavtsev, A., Pramatarov, P., Stefanova, M., and Khromov, N., "J. Instrum.," 2012, vol. 7, p. 07002. https://doi.org/10.1088/1748-0221/7/07/P07002
13. Yuan, C., Kudryavtsev, A.A., Saifutdinov, A.I., Sysoev, S.S., Stefanova, M.S., Pramatarov, P.M., and Zhou, Z., "Phys. Plasmas," 2018, vol. 25, p. 104501. https://doi.org/10.1063/1.5026214
14. Saifutdinov, A.I. and Sysoev, S.S., "Plasma Sources Sci. Technol.," 2021, vol. 30, no. 1, p. 017001. https://doi.org/10.1088/1361-6595/abd61d
15. Godyak, V.A. and Alexandrovich, B.M., "J. Appl. Phys.," 2015, vol. 118, p. 233302. https://doi.org/10.1063/1.4937446
16. http://www.plasmasensors.com/products.html#mfpa.
17. Impedans Langmuir Probe Measurement System, Exploitation Manual. Accessed August 26, 2016.
18. https://www.hidenanalytical.com/wp-content/uploads/2020/05/ESPion-pdf.pdf.
19. Ryabyi, V.A. and Obukhov, V.A., "Prikl. Fiz.," 2012, no. 5, p. 46.
20. Tsendin, L.D., "Plasma Sources Sci. Technol.," 1995, vol. 4, p. 200. https://doi.org/10.1088/0963-0252/4/2/004

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