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Mode Transition in a Low-pressure RF Capacitive Discharge in Nitrogen

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Abstract

Two different plasma modes of capacitive coupled rf (13.56 MHz) discharge in pure nitrogen were studied. The modes differed significantly in a visual appearance, plasma potential and in the shape of the electron energy distribution function (EEDF), which was caused by changes in processes at a grounded electrode. In the unconfined mode the electron density at the grounded electrode was controlled by diffusion like in the α mode of discharges, while the second, confined mode, was γ mode. For the plasma diagnostics we used Langmuir probe, Plasma Process Monitor, optical emission spectroscopy and we carried out electrical measurements on reactor with the discharge. Our investigations differed from the previous research in this field mainly by lower value of pressure used.

Introduction

In spite of a wide utilization of discharges in nitrogen and crucial influence of discharge mode on many applications, there was only small attention payed to the transition from α to γ mode [1]. This transition was more often investigated in argon [2, 3]. We studied mode transition in pure nitrogen at low pressure ($1-3$ Pa).

Experimental

Rf capacitively coupled nitrogen discharges were studied in a spherical (i. d. 250 mm) stainless steel reactor with two parallel-plate stainless steel electrodes separated by 57 mm. The bottom electrode (diameter 100 mm) was grounded. The upper electrode (diameter 80 mm) was driven at 13.56 MHz. In most of the measurements we used nitrogen flow of 25.3 sccm which corresponded to the pressure of 2.5 Pa. The rf power delivered by the generator varied from 10 to 45 W. Electrical measurements (rf voltage, rf current and a dc self-bias voltage on the driven electrode) were made on the coaxial cable between power unit and the driven electrode. For diagnostic purposes we used a Langmuir probe (Scientific Systems Ltd.) and the Plasma Processes Monitor PPM 421 (Balzers). The tip of the probe was placed at the discharge axis.

Results

Two different plasma regimes were observed. The first regime (further "unconfined mode") was diffusive and the thickness of the sheath between plasma and the grounded electrode was very thin (about 1 mm). In the second case (further "confined mode")

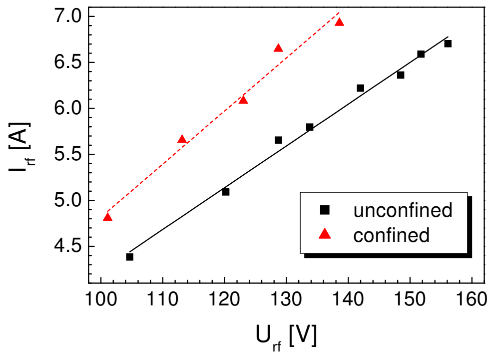

Figure 1: Current-voltage characteristics of rf nitrogen discharge in two modes

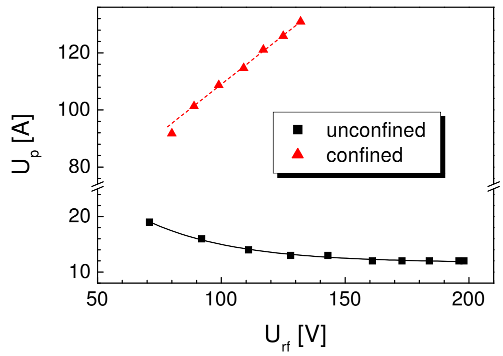

Figure 2: Plasma potential as a function of applied rf voltage amplitude

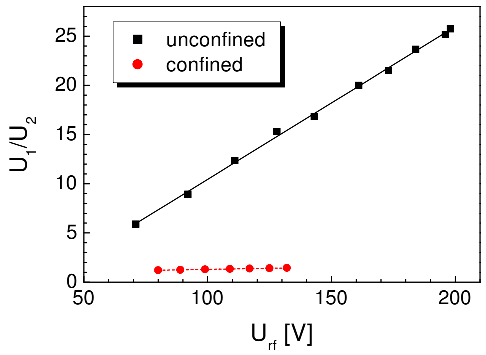

Figure 3: The ratio of sheath voltages for two discharge modes

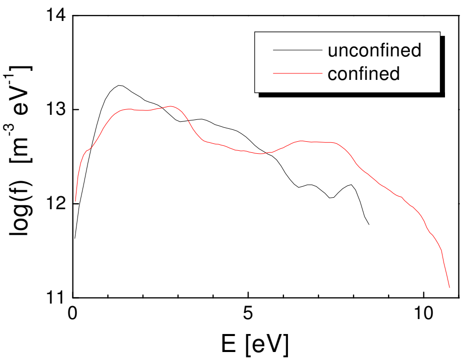

Figure 4: The decimal logarithm of the EEDF in two modes at 2.5 Pa

the thickness of the dark sheath at the grounded electrode was about 15 mm and the discharge was more confined between the electrodes. The sheath between plasma and the driven electrode was in both the modes similar to the sheath at the grounded electrode in the confined mode.

The unconfined mode was stable at lower rf power. After the power had been amplificated (maximum 45 W), the discharge regime changed abruptly. When now the rf power was decreased, the discharge remained first in the confined mode and than (at minimum power of 10 W) was the regime abruptly changed back to the unconfined mode.

The current-voltage characteristics of the system of reactor and discharge is shown in Fig. 1. The sheath voltage at the driven electrode U_1 (from 100 to 300 V) is not significantly influenced by the mode transition (Fig. 2). However, the plasma potential U_p and the ratio of sheath voltages by the driven and the grounded electrodes (U_1/U_2) change strongly (Fig. 3).

The position of the Langmuir probe in a series of measurements was 22 mm above the grounded electrode. The shape of the EEDF changes by the transition significantly (Fig. 4). In the confined mode there is an electron group with high energy. This electron group is stronger at lower pressures. When the probe was shifted to the grounded elec-

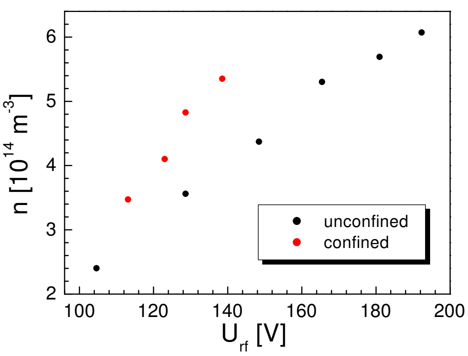

Figure 5: The electron density calculated from the integral of the EEDF

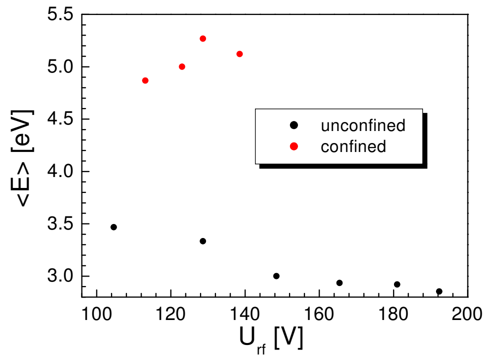

Figure 6: The average electron energy calculated using integral of the EEDF

trode, the shape of EEDF did not really changed in the unconfined mode. After the probe was shifted to the driven electrode, a lot of electrons with high energy (up to 70 eV) was observed. In the confined mode an electron group with high energy (about 25 eV) was observed near the grounded electrode too. The measured EEDF could not be fitted by standard distribution function, therefore we evaluated the electron density and the mean electron energy directly integrating the EEDF. The probe measurements were performed in the pressure range 1–3 Pa. In both discharge modes the electron density increased and the average electron density decreased with increasing pressure.

The measurement of the ion energy distribution was in fact successful only in the unconfined mode. In this mode the maximum energy of ions impinging on the grounded surface agreed relatively well with plasma potential determined from the probe measurements [4].

Optical emission spectroscopy was used to measure relative light intensity and to determine rotational and vibrational temperature (through 2nd positive system of nitrogen) in the centre of the discharge. Neither rotational nor vibrational temperature was significantly influenced by the regime transition. A little increase of the light emission intensity of pursued rotational bands (N_2, 2nd posit. system, 0–2 and N_2^+ $B^2\Sigma_u^+ - X^2\Sigma_g^+$, 0–0) by the transition was observed.

Discussion

The probe measurements near the electrodes demonstrate that in the sheath at the driven electrode the γ processes with following avalanche ionization take place in both discharge modes. In the unconfined mode the electron density near the grounded electrode is controlled by diffusion like in α discharge modes. Thanks to the low thickness of the sheath and discharge diffusion to the reactor walls (increasing area of grounded electrode) the ratio U_1/U_2 is high [5, 6]. In the confined mode the processes in the sheath at the grounded electrode are in principle the same, as in the sheath at the driven electrode - it is usual

γ mode. Observed transition is therefore close to the $\alpha - \gamma$ transition.

During the quick mode transition the discharge feature and properties change abruptly. Due to the avalanches in the sheath at the grounded electrode the electron density increases (Fig. 5). Compared with previous research the electron density is low. It is caused by the low value of the product of pressure and the electrode distance (p.d) implying strong diffusion and recombination on electrodes and walls. Due to an increase of plasma conductivity and emphasis of the sheath, the electric field intensity in inner part of the discharge decreases. Therefore in previous articles the average electron energy in the plasma centre is lower in the γ mode than in the α mode. Because of the low value of p.d fast electrons penetrate in our case from sheaths to the discharge centre and therefore we observed higher mean electron energy in the γ (confined) mode than in the unconfined mode (Fig. 6). Due to the low electron density and the presence of the high energy electron group the shape of EEDF is far away from Maxwellian distribution.

The increase of electron density with pressure is in both regimes caused by increase of the ionization frequency. The increase of plasma conductivity and collision frequency cause a decrease of the mean electron energy decreases.

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