Plasma Ionization in Low-Pressure Radio-Frequency Discharges—Part I: Optical Measurements

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***Abstract*—The electron dynamics in the low-pressure operation regime (< 5 Pa) of a neon capacitively coupled plasma is investigated using phase-resolved optical emission spectroscopy. Plasma ionization and sustainment mechanisms are governed by the expanding and contracting sheath and complex wave–particle interactions. Electrons are energized through the advancing and retreating electric field of the RF sheath. The associated interaction of energetic sheath electrons with thermal bulk plasma electrons drives a two-stream instability also dissipating power in the plasma.**

***Index Terms*—Capacitively coupled plasmas, electric field reversal, phase resolved optical emission spectroscopy, plasma diagnostics, plasma ionization, radio-frequency plasmas, wave-particle interaction.**

RECENT RESULTS have revealed that plasma ionization and sustaining mechanisms in low-pressure (< 5 Pa) capacitively coupled plasmas (CCPs) can be rather complex [1], [2]. Heating mechanisms in this pressure regime have long been a major topic of intense research with still many unresolved open questions [3]–[9]. This has been due to the complex nature of the mechanisms requiring specialized diagnostics with high spatial and temporal resolution, only recently available through modern technology [10]–[12]. It has been shown that complex interactions of the expanding plasma sheath with the plasma bulk are important ionization mechanisms in low-pressure hydrogen CCPs [1], [2]. Electrons are energized through wave–particle interactions at the sheath edge. It could be shown through both experimental results and particle in cell simulations that such discharges are an opportunity for fundamental laboratory investigations of nonlinear wave–particle interactions.

An experimental setup is developed for controlled fundamental investigations. The experimental system is a highly asymmetric capacitively coupled radio-frequency driven discharge. The discharge system consists of one flat powered electrode with no counterelectrode. The chamber wall is grounded. A large sheath potential forms at the powered electrode, and very little of the applied voltage is dropped across the sheath in front of the grounded chamber wall. Thus, a large dc self-bias develops at the powered electrode. This design ensures the minimal interaction of the two plasma boundary sheaths in the system. In this paper, the plasma is operated in neon, a noble gas with simpler plasma chemistry; in particular, the ion sheath chemistry is not as complex as that of the hydrogen plasma in the previous work [13]. The RF frequency is reduced to 2 MHz compared to 13.56 MHz for increased temporal resolution within the RF cycle. Low RF powers are used to avoid the discharge operating in gamma mode. Under the conditions investigated here, the plasma density and sheath voltages are low; thus, the ion flux and energy onto the electrode is low. Therefore, secondary electrons are avoided.

Phase-resolved optical emission spectroscopy (PROES) provides noninvasive access to the dynamics of high-energy electrons with excellent spatial and temporal resolution, on a nanosecond time scale. A detailed description of a typical PROES setup can be found in [14]. The PROES setup consists of a fast gate-able intensified CCD camera (ICCD) with an electronically tunable spectral filter (VariSpec CRI) for the discrimination of the Ne $2p_1$ emission line, which is primarily excited out of the ground state. The ICCD camera is synchronized with the RF generator powering the discharge. In this paper, we use a gate width of 2 ns for investigations within the 2-MHz cycle (RF period of 500 ns). A variable delay between the camera gate and the RF voltage allows for phase-resolved measurements within the RF cycle. From the measured phase-resolved emission, the excitation is determined using a deconvolution with the lifetime of the excited state [15].

Fig. 1 shows the spatiotemporal excitation in a neon 2-MHz discharge in front of the powered electrode for an applied peak-to-peak voltage of 790 V at 2 Pa. The plot represents one 2-MHz RF cycle and shows a region of 150 mm in front of the powered electrode. This excitation plot represents electrons with energies greater than the 19-eV excitation energy of neon. The yellow color illustrates regions of higher excitation.

The maximum extension of the sheath can be observed at a phase of 400 ns and is about 8 cm. At around 100 ns, the sheath collapses toward the electrode and associated with it is high excitation. This is followed by a very large excitation as the sheath expands into the plasma followed by several excitation bursts along the sheath edge. These bursts are observable as a series of bright and dark regions at about 10 cm.

The origin of these various excitation structures is now discussed in more detail. As the sheath retreats toward the

Manuscript received December 1, 2007; revised April 10, 2008.

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Digital Object Identifier 10.1109/TPS.2008.927348

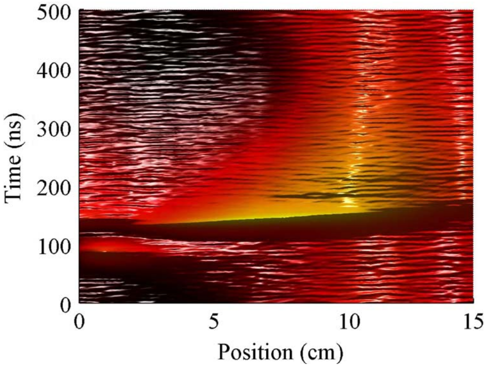

Fig. 1. Space- and phase-dependent excitation measured in the experiment, over one 2-MHz RF cycle, close to the powered electrode, at 2 Pa for 790 V of peak-to-peak voltage. The yellow regions denote high excitation.

electrode at a phase of 100 ns, electrons are accelerated with it. The electrons are accelerated in a local field, gaining enough energy to exceed the excitation threshold. This is a so-called field reversal, and similar structures were also observed in [1]. Field reversals have previously been measured, in hydrogen and electronegative plasmas [15]–[19] however not in rare gas discharges as is the case here. The origin of this field in the present 2-MHz noble gas discharge is different to that observed in the hydrogen and electronegative plasmas. In the low-pressure 2-MHz plasma, the sheath width is relatively large (due to low plasma density) as mentioned previously and collapses rapidly due to the relatively large distance it needs to bridge. The thermal velocity of electrons does not allow them to simply diffuse with the collapsing sheath, and thus, a region of space charge that accelerates electrons toward the electrode builds up. As soon as enough electrons balance the total positive charge loss from the plasma over the RF period, further electron loss to the surface is prevented through an electric field that reflects electrons.

After the sheath collapses the external potential and sheath electric field rise, electrons are accelerated from the electrode into the plasma bulk and can be observed as an excitation maximum around 150 ns. Immediately following this is a series of oscillations at the plasma sheath–bulk interface around 10 cm. These are due to an interaction of energetic electrons streaming into thermal bulk electrons [1]. The unstable interaction at the sheath edge gives rise to an electron–electron two-stream instability driving a large amplitude electron wave resulting in ionization and excitation observable in Fig. 1. The associated large amplitude electron waves result in power dissipation through electron trapping and phase mixing. This interaction is not damped by collisions at the low pressure and extends for a few hundred nanoseconds. These wave–particle interactions are an important excitation and, thus, ionization mechanism for sustaining the plasma at low pressures.

The excitation features observed in this new optimized experimental setup are qualitatively similar to those of previous work in hydrogen. This now gives us a simple test bed for more detailed fundamental investigations of wave–particle interaction and will be investigated in conjunction with a specifically designed particle-in-cell simulation (see Part II of this paper).

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