Plasma parameter evolution in a periodically pulsed ICP

V. Godyak and B. Alexandrovich

OSRAM SYLVANIA, 71 Cherry Hill Drive, Beverly, MA 01915, USA

The electron energy probability function (EEPF) has been measured in inductively coupled plasma (ICP) operated in a periodically pulsed regime. Time resolved EEPF measurements were performed in the afterglow between pulses and basic plasma parameters (plasma density and effective electron temperature) were found as appropriate integrals of the measured EEPF. When operated at the same average rf power, the periodically pulsed ICP was found to have a significantly larger plasma density and lower electron temperature than when operated in a CW mode.

1. Introduction

It has been known for a long time that a pulsed plasma has additional plasma parameter control over a steady state or CW operated discharge, which is limited by the plasma ionization and energy balance. In a steady state gas discharge at low gas pressure, particle balance requires the electron temperature T_e to be a function of the product pd, where p is the gas pressure and d is the characteristic plasma dimension: $T_e = T_e$ (pd).

In addition, the electron energy balance defines the electron heating electric field, E, maintained at some fixed equilibrium level that depends on pd:
E = E(pd). Both, T_e and E are practically independent of the discharge power P_d. The plasma conductivity that proportional to plasma density, n, is nearly proportional to the discharge current density J, so that $E \sim (P_d/n)^{1/2}$ keeps constant. In a steady state discharge, plasma density is in equilibrium with discharge power, thus, increase in discharge power does not lead to increase in the electric field and electron temperature. Actually, due to various non-linear processes in the plasma particle balance and in EEPF formation, both E and T_e slightly decrease with increasing discharge power. The origin of these non-linear processes is associated with rising plasma density.

When plasma is energized pulse-wise, by RF bursts of duration T_{on} , being much shorter than the time-off between the pulses T_{off}, and T_{off} is maintained shorter than the plasma diffusion time, T_d , ($T_{on} << T_{off} << T_d$), the plasma density does not have time to attain equilibrium, and, therefore, the electric field and electron temperature can exceed their equilibrium levels. Since the ionization rate is a sharply increasing function of electron temperature, the greater electron temperature during the pulse causes intense ionization that compensates plasma particle loss due to diffusion to the wall in the afterglow stage between pulses.

With the absence of a heating electric field in the afterglow stage, electrons cool down mainly due to electron diffusion to the chamber wall; the process known as diffusion cooling [1].

Interest in pulsed operation of rf plasmas was recently revitalized in the hope of achieving more flexibility in plasma parameter control in the plasma processing reactors [2-4]. A detailed study of the EEPF in ICP afterglows was performed in Ref. 3 where diffusion cooling was proven to be the major electron cooling process in argon ICP afterglow at 15 and 70 mTorr.

Results of an experimental study of the plasma parameter evolution in periodically pulsed ICP are presented in this paper. A significant enhancement in the plasma density and reduction in electron temperature are demonstrated for a periodically pulsed mode when compared with a CW mode.

2. Experimental set-up

Measurements were performed in afterglow, during off-cycle in the ICP sustained in a metal chamber having the diameter 10 cm and length 12 cm. The plasma was energized by short bursts of rf power at 4 MHz using the internal helical antenna (2.2 cm diameter and 5 cm length having 12 turns) placed in the mid-plane along the chamber axis. The discharge power delivered to the plasma was calculated as the difference between the total power delivered to the antenna and the power dissipated in the antenna itself.

Probe measurements were performed at the discharge mid-plane, at radial position r = 5 cm, near the peak plasma density. Gas flow through the chamber- insuring gas purity - was controlled by a needle micro-valve at the gas inlet and by a diaphragm valve at the chamber downstream. This vacuum system allowed maintaining argon pressure within the chamber in the range from 3 to 300 mTorr.

The time resolved second derivative of the probe characteristic that is proportional to the electron energy probability function (EEPF) was measured with our station for fast probe measurement [5,6]. The procedure for acquiring the probe characteristic in periodically pulsed plasma includes formation of the probe bias voltage, that is updated in incremental steps on each new pulse, and continuous acquisition of the probe current waveform during the pulse period. Both, voltage generation and current acquisition are triggered by the pulse front. The data block, obtained during the period of one pulse, is the time-varying current at the given bias voltage. The number of samples acquired during the pulse period equals the sampling frequency to the pulse frequency ratio. Each new data block, obtained during a successive pulse, presents time-varying current at the updated level of the bias voltage. Consequently, the data that have the same index in each block (corresponding to the same instant within the period) are sorted together creating a single I-V characteristic for the given moment. Each I-V is processed separately to obtain an instant EEDF.

The probe station also incorporates feedback from a floating reference probe to reduce plasma-generated noise and compensate for voltage drop across the chamber wall sheath due to current collected by the probe.

The measurement-acquisition system used here provides time resolution of 0.5 μs. Acquisition of a hundred time-resolved EEDF's, each averaged over 100 samples takes less then 1 minute when the plasma is pulsed at 1 kHz rate. The enormous reduction in the processing time (1 minute compared to 5 hours in Ref. 3) not only saves time, but also reduces EEPF measurement distortions caused by plasma drift and by any changes in the work function of the probe surface during a slow scan of the probe voltage.

3. Experimental results and discussion

The values of T_e in the CW mode and the time evolution of T_e in a 100 W ICP afterglow (off-cycle) for different argon pressures are shown in Fig. 1. These data were obtained at 50% duty cycle, with the on-cycle long enough (1 ms) to reach steady state, then followed by the afterglow.

Fig. 1 shows that electron cooling is faster for lower argon pressure, suggesting that the diffusion cooling is the main mechanism of the electron energy loss in the afterglow [3], even at the highest gas pressure (300 mTorr).

In the late afterglow stage, T_e reaches very low values (up to 0.05 eV) that are close to the argon gas temperature. The minimum value of the electron temperature, found in the experiment, is probably limited by the resolution of EEPF measurement of our experimental apparatus.

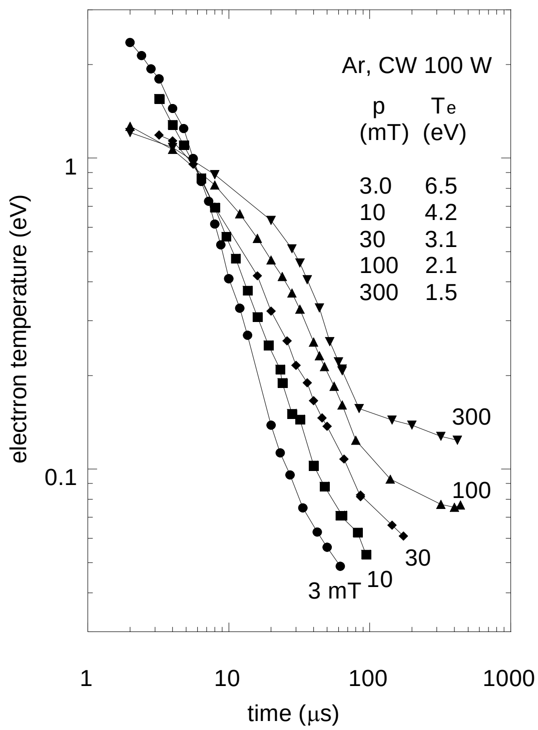

Fig. 1. T_e in the CW mode (table) and the EEPF in the afterglow

Electron temperature cooling occurs more rapidly at lower gas pressures, as plasma loss to the wall transits from collisional ambipolar diffusion at high pressure to that controlled by the ion inertia in the Tonks-Langmuir regime at low pressure.

The large span of electron temperature change during the afterglow suggests that the electron temperature can be controlled in the periodically- pulsed discharge by varying off-cycle time.

An example of such electron temperature control is demonstrated in Figs. 2 and 3 where time evolution of the measured EEPF, calculated values of the effective electron temperature, T_e, and the plasma density, n, are given for a 30 mTorr ICP at the average discharge power of 50 W (~ 550W peak). The measurements were made during the afterglow stage of a periodically pulsed ICP with on-time, T_{on} = 2 μs, and off-time, T_{off} = 20 μs. For comparison, the EEPF and plasma parameters for the same ICP in a CW mode with the same gas pressure and discharge power are given in Fig. 4.

Figs. 2, 3 and 4, show that the electron temperature in the afterglow stage is essentially lower than that in CW mode, and is a falling function of elapsed time.

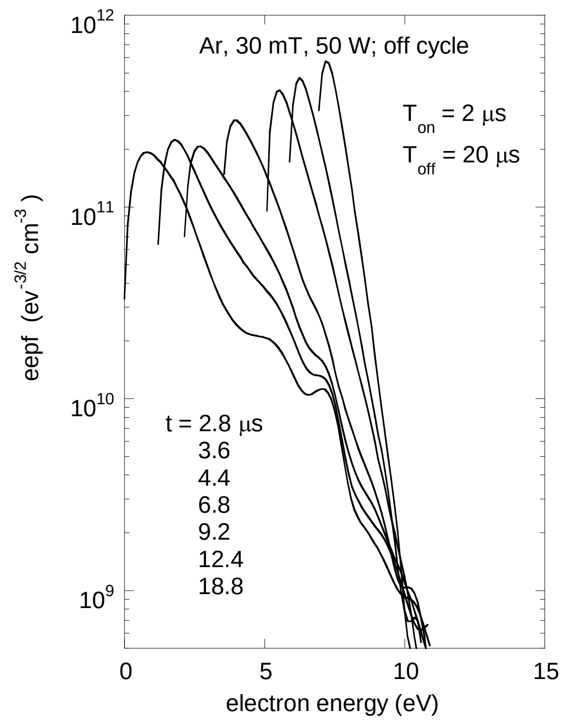

Fig. 2. The EEPF evolution in the afterglow stage. EEPFs are shown in order from left to right as the elapsed time, t. The shift in the EEPF position along the energy axis corresponds to the plasma potential shift, reference to the plasma potential at t = 2.8 µs.

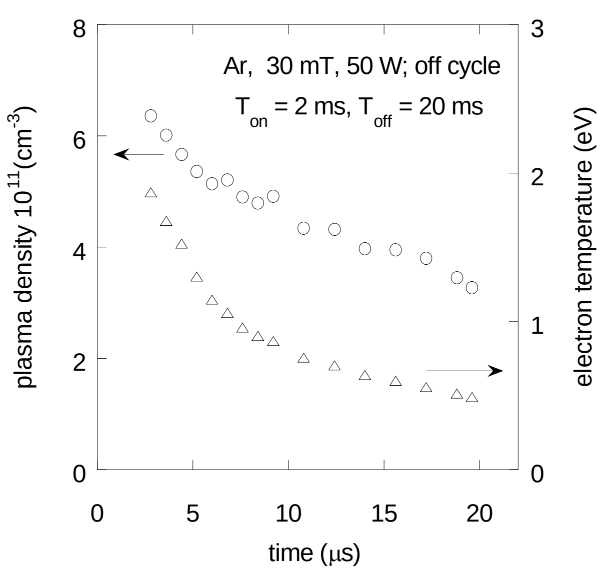

Fig. 3. Plasma parameters in the afterglow stage.

By the end of the afterglow period, the electron temperature is an order of magnitude less than that in the CW mode. Due to absence of the electric field and reduced electron temperature, the EEPF in the late afterglow stage is Maxwellian.

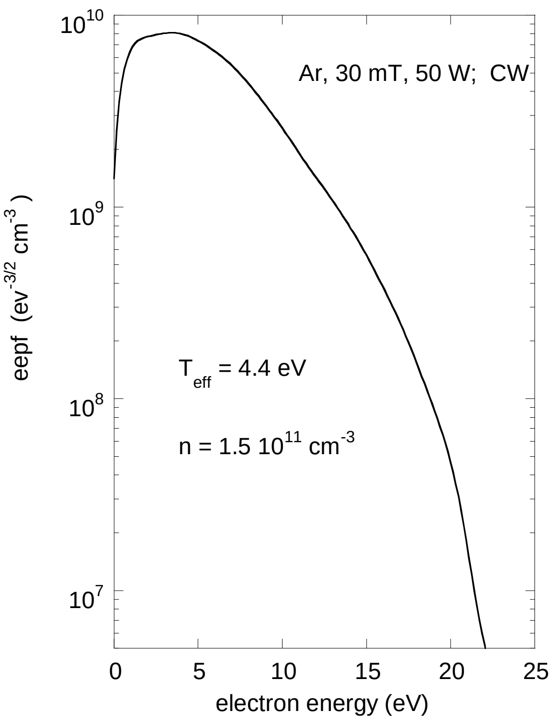

Fig. 4. EEPF and plasma parameters in the CW mode.

The lowest electron temperature in the afterglow stage is controlled by the afterglow duration. Thus, the time-averaged electron temperature can be controlled varying T_{off}.

The reduction in the time-averaged electron temperature in the periodically pulsed discharge is accompanied by the presence of high temperature electrons during on-cycle. Their effective electron temperature, T_{eff}, is expected to be higher than T_{eff} for the CW mode, because the electric field during on-cycle is higher than for CW.

Obtaining EEPF during on-cycle in present experiment was not possible, because the characteristic rise time of plasma density and, to an even larger extent, the rise time of the electron temperature were comparable to or less than the time resolution of our measurement apparatus.

Due to excess of high energy electrons during on-cycle and a their fast cooling during off-cycle (afterglow), the time averaged EEPF in a periodically pulsed discharge is expected to have a two-temperature structure, like the bi-Maxwellian EEPF found in a low pressure capacitive rf discharge [7]. Due to near-exponential dependence of the ionization rate on electron temperature (electron mean energy), only a moderate increase in T_{eff} during the pulse on-cycle could be anticipated comparing to T_{eff} in a CW mode. Therefore, for a typical case of periodically pulsed plasma ($T_{off} >> T_{on}$), the effective electron temperature, averaged over the period ($T_{on}+ T_{off}$), is always lower than T_{eff} in CW mode. Comparing electron temperatures and plasma densities for CW (Fig. 4) and periodically-pulsed ICP (Fig. 3), one can see that in the case of periodically-pulsed plasma the time averaged electron temperature, $<T_e> \approx 1$ eV, is considerably less, while the averaged plasma density $<n> \approx 5 \cdot 10^{11}$ cm^{-3} is considerably higher than those in CW mode. The reason for such significant difference in the plasma density is the intense ionization (plasma production) during on-cycle by the “overheated” electrons, and reduction (due to fast electron cooling) of plasma diffusion to the wall in the afterglow stage.

4. References

[1] M. A. Biondi, Phys. Rev. **93**, (1954).

[2] X. Tang and D. Manos, Plasma Source Sci. Technol. **8**, 594 (1999).

[3] A. Mareska, K. Orlov and U. Kortshagen, Phys. Rev. E **60**, 056405 (2002).

[4] S. Voronin, M. Alexander and J. W. Bradley, Meas, Sci. Technol. **15**, 2375 (2004).

[5] V. Godyak, R. Piejak and B. Alexandrovich, Plasma Source Sci. Technol. **11**, 525 (2002).

[6] B. Alexandrovich, V. Godyak and G. Lister, Proceedings of the 10th International Symposium on the Science and Technology of Light Sources, p. 283, editor. G. Zissis (Toulouse, France, July 2004).

[7] V. Godyak and R. Piejak, Phys. Rev. Lett. **65**, 996 (1990).