Evolution of the Electron-Energy-Distribution Function during rf Discharge Transition to the High-Voltage Mode

V. A. Godyak, R. B. Piejak, and B. M. Alexandrovich
GTE Laboratories Incorporated, Waltham, Massachusetts 02254
(Received 26 August 1991)

The electron-energy-distribution function (EEDF) in low-pressure argon and helium rf discharges has been measured during the discharge transition from the low-voltage to the high-voltage mode using a recently developed high-resolution Langmuir probe technique. When the transition occurs, the EEDF becomes Maxwellian because of increased electron-electron collisions arising from a sharp rise in electron density and a steep fall in electron temperature caused by γ-electron injection.

PACS numbers: 52.40.Hf, 52.80.Pi

A distinct feature of capacitively coupled rf discharges is the existence of two operational modes which dramatically differ in light emission and, in some cases, in electrical characteristics. This behavior was first reported by Levitskii [1] who hypothesized that these two distinct discharge modes differ in their governing ionization processes. According to Levitskii, at low rf discharge voltages ionization is provided by plasma electrons and the discharge is in the α mode, as in the positive column of a dc discharge, while at high discharge voltages (and power) ionization is maintained by fast electrons initiated at the rf electrodes and the discharge is in the γ mode, as in the negative glow region of a dc glow discharge. An experimental study of rf discharges in the γ mode using Langmuir probes [2] showed that the transition into the γ mode is accompanied by a sharp drop in the electron temperature T_e and a sharp rise in the plasma density n. This behavior was found to be in reasonable agreement with predictions from a two-dimensional hydrodynamic model [2] of an rf discharge in the γ mode based on an assumption of two electron groups.

Here, we report on electron-energy-distribution-function (EEDF), $F(\varepsilon)$, measurements in argon and helium rf discharges and for the first time demonstrate the evolution of the EEDF as the discharge goes from the α mode to the γ mode of operation. The EEDF was measured in the midplane on the axis of a symmetrically driven rf (13.56 MHz) discharge maintained between two parallel-plate aluminum electrodes separated by 6.7 cm and radially confined by a glass wall with an inner diameter of 14.3 cm. The EEDF and the discharge parameters were measured with the arrangement described in Ref. [3].

The evolution of the electron probability function (EEPF), $f(\varepsilon)=\varepsilon^{-1/2}F(\varepsilon)$, the plasma parameters, and the discharge parameters are shown in Fig. 1 for argon and in Fig. 2 for helium at a gas pressure of 0.3 Torr. In both gases, for relatively small discharge currents, the EEPF's do not change shape appreciably with growing discharge current, remaining Druyvesteyn-like, $f(\varepsilon)\propto\exp(\varepsilon/eT)^2$, in argon, and Maxwellian-like, $f(\varepsilon)\propto\exp(\varepsilon/eT)$, in helium, where T is a parameter equal to the electron temperature for a Maxwellian distribution and e is the electron charge. The differences of the EEPF's in the energy interval below the inelastic threshold energy (11.6 eV in argon and 19.8 eV in helium) are due to the differences in the functionality of the elastic electron-neutral collision frequency $\nu_{en}(\varepsilon)$ for argon and helium [4].

With increasing discharge current, the effective electron temperature $T_{e\,\mathrm{eff}}$ in the low-current mode is almost unchanged, while the plasma density in the discharge center n_0 grows linearly. The trends in the behavior of $T_{e\,\mathrm{eff}}$ and n_0 imply that the rf electric field in the plasma body, $E_0=(\nu_{en}+j\omega)mJ/e^2n_0$, is nearly constant, as one expects in a weakly ionized self-sustained dc or rf discharge (here m is the electron mass, ω is the driving frequency, and J is the discharge current density; note that at $p=0.3$ Torr, for both gases, $\omega^2\ll\nu_{en}^2$). Further increase in the discharge current leads to a transition into the γ mode accompanied by dramatic changes in the EEPF and in the plasma parameters, $T_{e\,\mathrm{eff}}$ and n_0. In both gases, the EEPF becomes Maxwellian with a considerably reduced $T_{e\,\mathrm{eff}}$ and n_0 grows much faster than a linear rate with respect to discharge current. The steep rise in the plasma density (and conductivity) due to γ-electron ionization results in a sharp drop in T_e. The drop in T_e and jump in n_0 both result in a drastic increase in the electron-electron collision frequency, $\nu_{ee}\propto n_0/T_e^{3/2}$, that, together with the reduced plasma rf field, makes a strong argument for a Maxwellian distribution. Thus, comparing the discharges in the α mode at $J=1$ mA/cm^2 and in the γ mode at $J=10$ mA/cm^2, one finds that ν_{ee} increases by a factor of 300 in argon and a factor of 2000 in helium, while the discharge current density increases only by a factor of 10.

In the γ mode of a helium rf discharge, the measured EEPF reveals a tail of high-energy electrons and the EEPF can be represented as a sum of two Maxwellian distributions with temperatures for the cold-electron group T_{ec} and the hot-electron group T_{eh}, with corresponding electron densities $n_{ec}\approx n_0$ and n_{eh}, respectively. In Table I these parameters are given together with calculated values of T_{ec}^1 for different discharge current densities.

Although the decrease in the plasma rf field in the γ

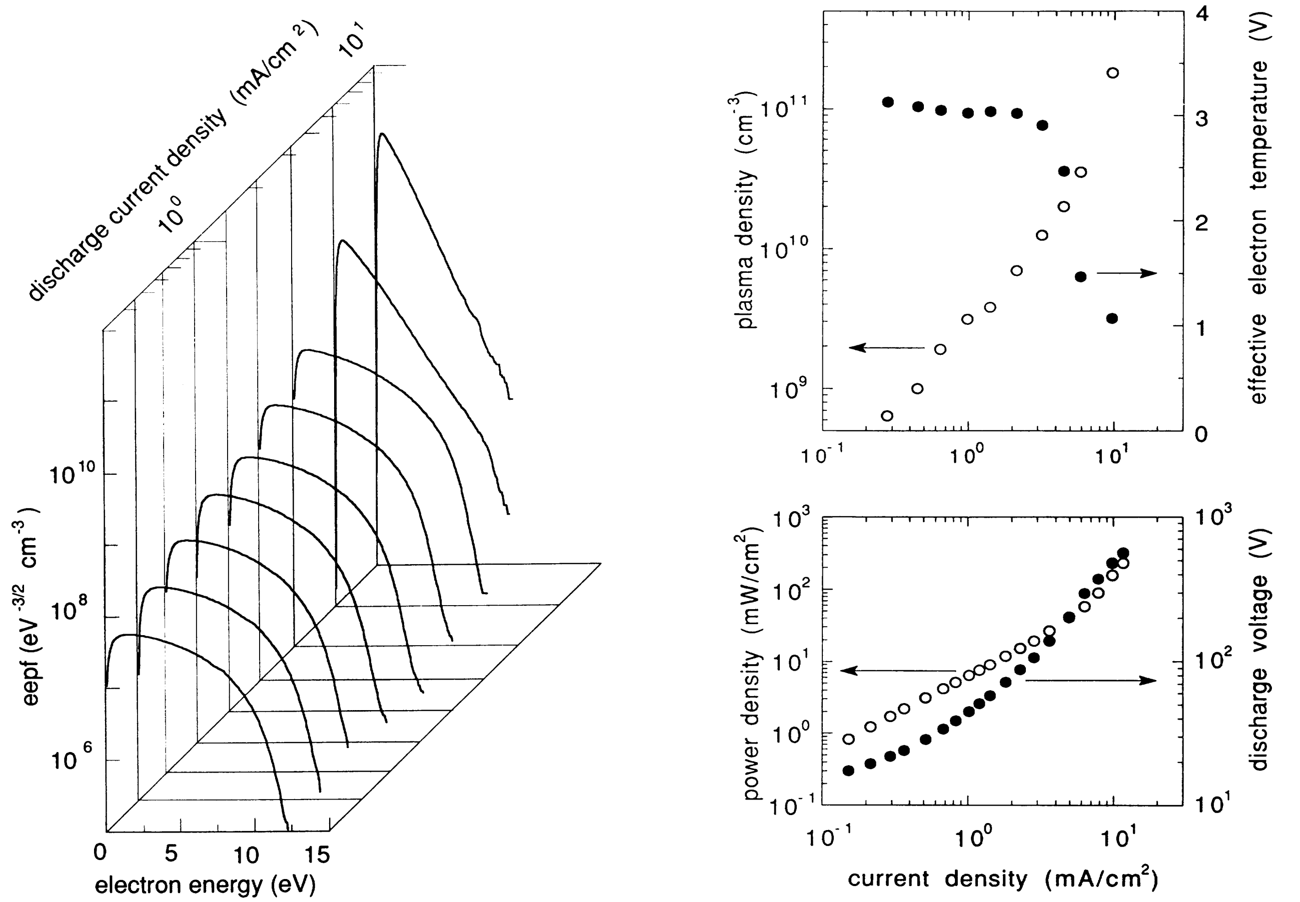

FIG. 1. Evolution of EEPF, plasma, and discharge parameters with increasing discharge current for an argon rf discharge, $p = 0.3$ Torr.

mode causes the electron temperature to drop, well into the γ mode ($J = 10$ mA/cm^2) the measured temperature of cold electrons T_{ec} is significantly higher than the equilibrium electron temperature,

$$T_e(E) = T_g + (J/en_0)^2 M/6e \,,$$

found from the local electron-energy balance between Ohmic heating and elastic-collision losses (here M and T_g are the mass and the temperature of the gas atoms, respectively). Based on experimental data at $J = 10$ mA/cm^2 and assuming $T_g = 0.03$ V, the values of $T_e(E)$ are found to be 0.71 V for argon and 0.058 V for helium while measured values are 1.1 and 0.5 V, respectively. This difference suggests an additional electron heating process which may be energy transfer from the high-energy electron group by means of electron-electron collisions, as has been shown for the negative glow region of a dc glow discharge [5].

Electron temperatures T_{ec}^{1} given in Table I were found from an energy balance of the low-energy electrons [5] accounting for both local Ohmic heating and heating by fast electrons and are in good agreement with the experimental data for T_{ec}. Nonetheless, this agreement is believed to be somewhat fortuitous since the measurements of the EEPF tail corresponding to high-temperature electrons may be significantly distorted by ion probe current giving the appearance of an excessive number and a distorted energy distribution of high-energy electrons. In addition, at conditions in these experiments, electron heating at the plasma boundaries near the rf sheath can significantly contribute to the energy balance in the plasma midplane where the measurements were made, since at the plasma boundaries the rf field collisional heating is essentially larger than that in the midplane ($E^2 \propto n^{-2}$ and $n < n_0$) and the energy relaxation length for cold electrons, $\lambda_\varepsilon = \lambda_e (2m/M + \nu_{ee}/\nu_{en})^{-1}$, is larger than the plasma half-width (λ_e is the electron mean free path for electron-neutral collisions). Thus, there is a strong argument for nonlocal coupling between the electron energy at the discharge midplane and inhomogeneous rf heating near the sheaths and the agreement found between the measured T_{ec} and that calculated T_{ec}^{1} from the local approach seems to be the result of mutual compensation in overestimating heating by fast electrons and underestimating the nonlocal collisional heating.

It was not possible to analyze the high-energy γ elec-

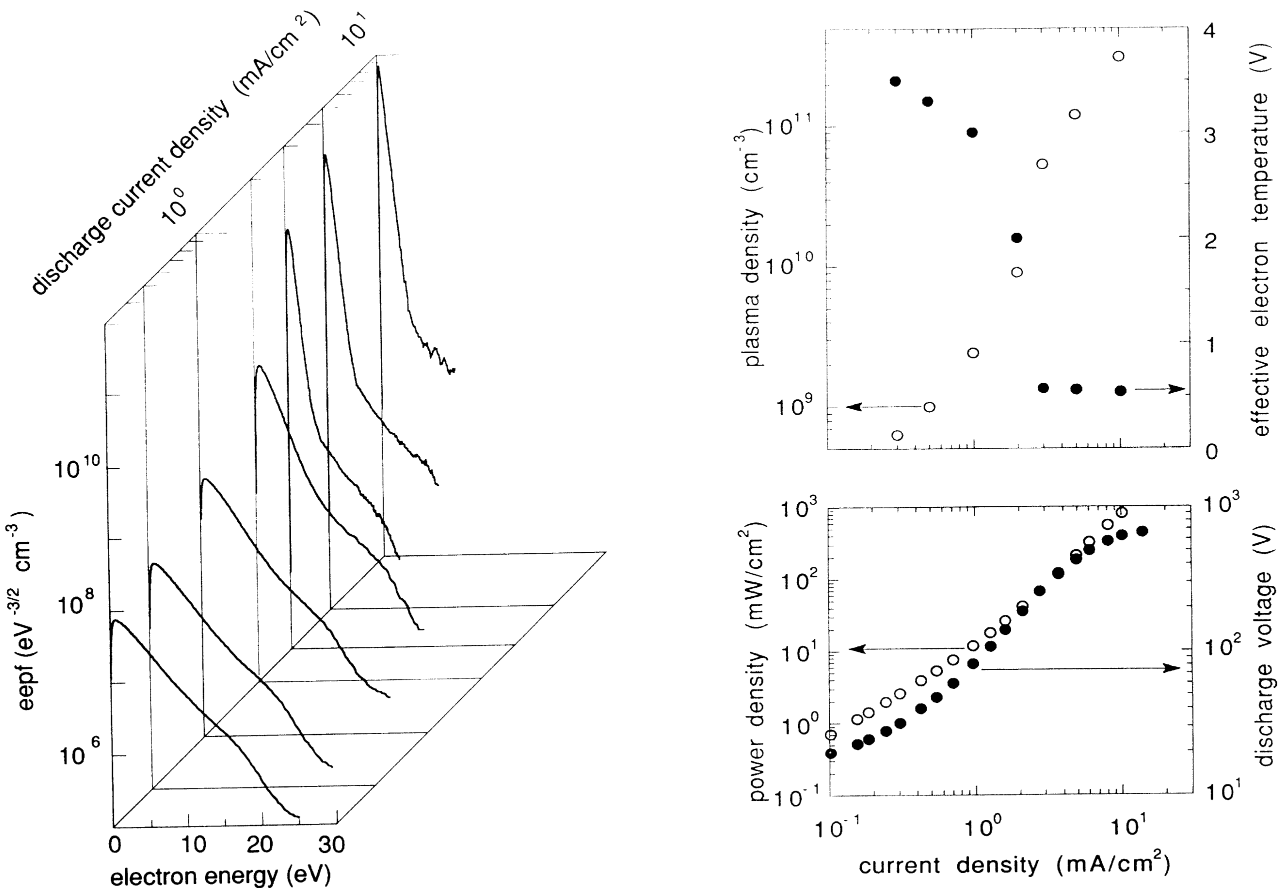

FIG. 2. Evolution of EEPF, plasma, and discharge parameters with increasing discharge current for a helium rf discharge, $p = 0.3$ Torr.

trons which presumably perform ionization and gas excitation. Having an effective temperature comparable to the rf sheath voltage, the γ electrons accelerated in the rf sheaths have a high ionization efficiency and thus the ionization balance of an rf discharge in the γ mode requires only an extremely small number of γ electrons [2]. The limited dynamic resolution (about 4 orders of magnitude) in the EEPF measurement and the masking effect of the ion current make detection of γ electrons with probe techniques highly problematic.

The transition point where the discharge switches from the α mode to the γ mode, defined as the steepest part of the $T_{e\,\mathrm{eff}}(J)$ dependence, corresponds to a transition current density J_{tr} and a transition voltage V_{tr} of 5 mA/cm^2 and 200 V for argon and 2 mA/cm^2 and 180 V for helium respectively. These transition voltages are comparable to the normal cathode fall voltage in a dc glow discharge. For both gases V_{tr} correlates well with a change in the discharge color (luminosity) observed in experiment. However, as one can see in Fig. 2 for helium, the departure from linear current/voltage characteristics (which further leads to the discharge voltage saturation) takes place somewhere between 400 and 500 V which is more than twice larger than V_{tr} found from the $T_{e\,\mathrm{eff}}(J)$ dependency. No trend in the discharge voltage saturation is seen in argon although changes in the EEPF and in the discharge luminosity are evident. The difference between V_{tr} found from the $T_{e\,\mathrm{eff}}(J)$ dependence and the departure from linear current/voltage characteristics has also been found in helium rf discharges driven at 3.2 MHz [2]. This observation reflects the fact that γ-electron injection to the plasma precedes the development in the rf sheaths of an electron avalanche which leads to rf sheath contraction. The sheath contraction increases the rf sheath capacitance and results in saturation of the discharge voltage. The rf sheath contraction is similar to that in the dc glow discharge as it evolves from the normal glow mode to the abnormal glow mode.

TABLE I. EEPF parameters for a helium rf discharge in the γ mode.

J (mA/cm^2)	n_0 (10^{11} cm^{-3})	$T_{e\,\mathrm{eff}}$ (V)	n_{eh} (10^9 cm^{-3})	T_{eh} (V)	T_{ec} (V)	T^1_{ec} (V)
3	0.53	0.57	1.4	3.3	0.47	0.49
5	1.2	0.56	1.8	4.0	0.44	0.54
10	3.1	0.54	2.4	3.9	0.50	0.62

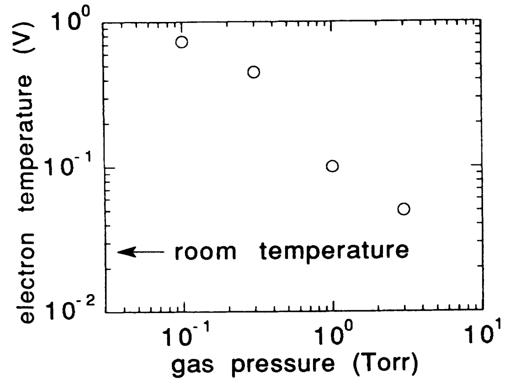

FIG. 3. Electron temperature vs gas pressure for a helium rf discharge in the γ mode, $J=10$ mA/cm^2.

The electron temperature of the main body of electrons T_{ec} measured in a well developed γ mode (at $J=10$ mA/cm^2), when T_{ec} reaches its minimum value, is shown in Fig. 3 as a function of the helium gas pressure. The fall in the electron temperature with increasing gas pressure is a consequence of the change in the electron-energy balance mainly due to a drop in the electron heating power. Increase in the gas pressure results in an exponential decay in the number of fast electrons reaching the plasma midplane [2] and a reduction in the heat transfer from the plasma boundaries to the center, thereby providing conditions for a local equilibrium between T_{ec} and E_0. As shown in Ref. [2], $n_0 \propto p^2$ in the γ mode. Between $p=0.3$ and 3 Torr the experiment gives $T_{ec} \propto p^{-1}$ (see Fig. 3). In this pressure range, the electron recoil rate (due to elastic collision) $\propto p^{-1/2}$ drops ~ 3 times, while the rf field heating rate $\propto p n_0^{-2} T_{ec}^{1/2} \propto p^{-7/2}$ drops ~ 3000 times. Thus, at high gas pressures the swarm of fast γ electrons generated in the rf sheaths quickly decays in the plasma providing ionization only near the plasma boundaries. From there, the cold electrons produced by the γ electrons diffuse to the plasma center and vanish due to radial diffusion and/or recombination. The last process is very probable due to the extremely low electron energy. The picture described here is equivalent to that in the Faraday dark space of a dc glow discharge.

The electron temperature of 52 mV (or 600 K) measured at 3 Torr is close to that typically found in the negative glow of a dc discharge and it is close to the radiation temperature in a helium rf discharge ($p=0.5$ Torr, $f=2.5$ MHz) found from microwave diagnostics [6].

In conclusion, we note that the electron temperatures found here from EEDF measurements are significantly lower than those found in Ref. [2]. The main reason for this difference is essentially an improvement in the energy resolution of the developed probe measurement system [3].

[1] S. M. Levitskii, Zh. Tekh. Fiz. **27**, 1001 (1957) [Sov. Phys. Tech. Phys. **2**, 887 (1957)].

[2] V. A. Godyak and A. S. Khanneh, J. Phys. (Paris), Colloq. **40**, C7-125 (1979); **40**, C7-197 (1979); IEEE Trans. Plasma Sci. **14**, 112 (1986).

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

[4] E. V. Karoulina and Yu. A. Lebedev, J. Phys. D **21**, 411 (1988).

[5] J. E. Lawler, E. A. Den Hartog, and W. N. G. Hitchon, Phys. Rev. A **43**, 4427 (1991).

[6] G. A. Hebner, J. T. Verdeyen, and M. J. Kushner, J. Appl. Phys. **63**, 2226 (1988).