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Direct current glow discharges in atmospheric air

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Direct current glow discharges have been operated in atmospheric air by using 100 μm microhollow cathode discharges as plasma cathodes. The glow discharges were operated at currents of up to 22 mA, corresponding to current densities of 3.8 A/cm^2 and at average electric fields of 1.2 kV/cm. Electron densities in the glow are in the range from 10^{12} to $10^{13}\,\mathrm{cm}^{-3}$. Varying the current of the microhollow cathode discharge allows us to control the current in the atmospheric pressure glow discharge. Large volume atmospheric pressure air plasmas can be generated by operating microhollow cathode discharges in parallel.
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Research on high-pressure glow discharges is motivated by applications such as instantly activated reflectors and absorbers for electromagnetic radiation, surface treatment, thin-film deposition, remediation and detoxification of gaseous pollution, and gas lasers. Many of these applications require the generation of air plasma at atmospheric pressure with electron densities exceeding $10^{11}\,\mathrm{cm}^{-3}$. One of the major obstacles in obtaining such a plasma are instabilities, particularly glow-to-arc transitions (GAT), which lead to the filamentation of the glow discharge in times short compared to the desired lifetime of a homogeneous glow. These instabilities generally develop in the cathode fall, a region of high electric field, which in self-sustained glow discharges is required for the emission of electrons through ion impact. Eliminating the cathode fall, by supplying the electrons by means of an external source, is therefore expected to extend the range of stable operation.

Recently, it has been shown that microhollow cathode discharges (MHCDs) serve as electron emitters for high-pressure glow discharges.[1] Microhollow cathode discharges are high-pressure, direct current glow discharges between closely spaced electrodes with an electrode opening of approximately 100 μm and an electrode distance of about 200 μm. Experiments in argon and xenon have shown that dc operation of microhollow cathode discharges in noble gases is possible at atmospheric pressure.[2,3] More recently, stable discharge operation has also been obtained in atmospheric pressure air.[4] When operated in the hollow cathode discharge mode electrons are extracted through the anode opening at moderate electric fields. These electrons support a stable plasma between the microhollow anode and a third positively biased electrode. Direct current glow discharges in argon at one atmosphere have been generated using this method.[1] As shown in the following, the microhollow cathode discharges can also be used to sustain dc glow discharges in atmospheric pressure air.

The electrode system used in our experiments consists of a microhollow electrode system and an additional electrode with variable distance of up to 10 mm from the microhollow anode. The electrode configuration and the experimental setup are shown in Fig. 1. Also shown are photographs of the microhollow cathode discharge in air (end-on) and the MHCD sustained glow between hollow anode and third electrode (side-on). The pressure was, in this case, 10 Torr. The microhollow cathode discharge is generated between two plane–parallel electrodes with centered circular openings. The electrodes consist of 100-μm-thin molybdenum foils and the cathode and anode hole diameter of the plasma cathode ranges from 80 to 100 μm. The dielectric is alumina (Al_2O_3, 96% purity) of 250 μm thickness and is placed as a spacer between the electrodes. The anode of the microhollow cathode geometry is on ground potential, the third electrode is biased positively with respect to the microhollow anode. It serves as anode for the microhollow cathode sustained (MCS) glow discharge. The sustaining voltage of the microhollow cathode discharge is in the range from 400 to 600 V depending on current, gas pressure, and gap distance. The MHCD current was limited to values of less than 22 mA dc to prevent overheating of the sample.

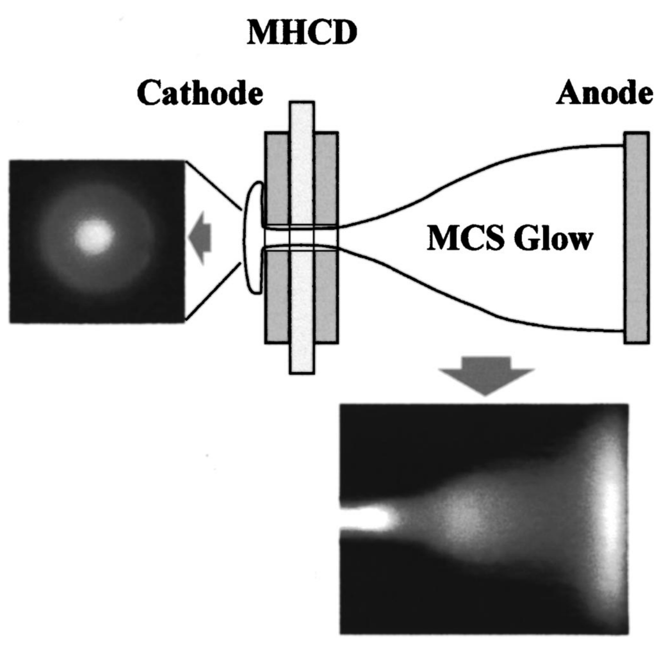

FIG. 1. Geometry of the microhollow electrode system with a third electrode and the appearance of the discharge plasma, end-on and side-on.

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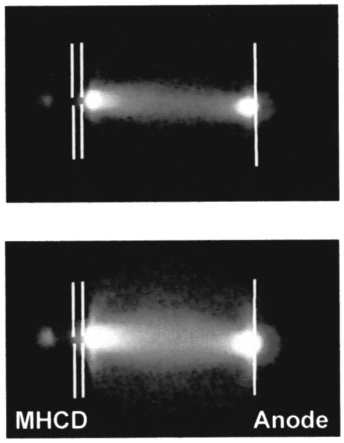

FIG. 2. MCS glow discharge in atmospheric air at two different current levels 8.7 and 22 mA, respectively, at 0.2 cm gap distance. Upper photograph: $V_{\mathrm{MHCD}}=499$ V, $I_{\mathrm{MHCD}}=8.9$ mA, $V_{\mathrm{MCS}}=250$ V, $I_{\mathrm{MCS}}=8.7$ mA. Lower photograph: $V_{\mathrm{MHCD}}=409$ V, $I_{\mathrm{MHCD}}=27.0$ mA, $V_{\mathrm{MCS}}=238$ V, $I_{\mathrm{MCS}}=22.0$ mA.

Since possible discharge instabilities like thermal instability or attachment instability[5] may occur on a time scale of microseconds and less, too fast to be observed with dc current and voltage monitors, we have in all measurements monitored the current and voltage by means of fast electrical probes and recorded the traces by means of a 400 MHz digital oscilloscope. In addition, the appearance of the dc discharge has been recorded by means of a charge-coupled device camera.

Figure 2 shows atmospheric pressure air discharges at two current levels of 8.7 and 22 mA, respectively. The air plasma is cylindrical with the diameter at the plasma cathode determined by the hole diameter (100 μm). At 8.7 mA the diameter increases to 430 μm in the midplane of the discharge gap, and then shrinks again to approximately the cathode diameter at the third electrode. At 22 mA the diameter in the midplane is about 860 μm. The current density is at the currents of 8.7 and 22 mA, and 6 and 3.8 A/cm^2, respectively.

Figure 3 shows the development of the MCS air glow discharge current with increasing MHCD current at atmospheric pressure. The voltage at the third electrode was kept constant at $V=250$ V. The MCS glow discharge current is identical to the plasma cathode current above the minimum

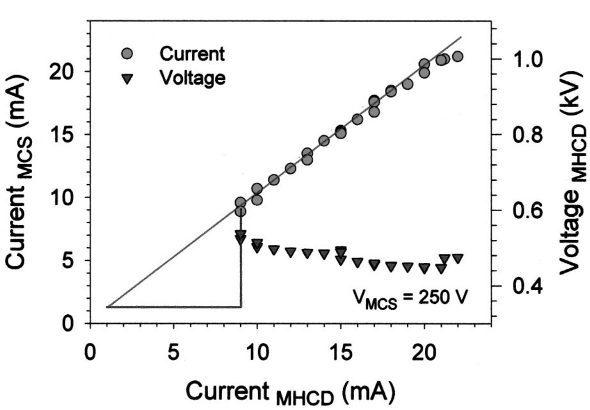

FIG. 3. MCS glow discharge current vs MHCD current and forward voltage vs current of the MHCD for constant voltage V_{MCS} at the third electrode.

sustaining current (8 mA) for the MCS discharge. The microhollow cathode discharge acts as a constant current source for the air glow. In this mode the forward voltage in the microhollow cathode discharge, which serves as the plasma cathode, decreases slightly with current (Fig. 3). Small variations in the MHCD voltage cause, therefore, large swings in the electron current, and consequently, the current in the air glow.

The electron density n_e can be estimated from the electrical parameters of the discharge, the electric field E, the current density j, and the electron mobility μ_e:

$$n_e=j/(E\mu_e e), \tag{1}$$

with e being the electron charge and μ_e obtained from

$$(\mu_e p)_{T_0}=0.45\times10^6 \ \ (\mathrm{cm^2\,Torr/V\,s}). \tag{2}$$

This equation holds for air[5] at room temperature T_0. Recent measurements showed that the gas temperature T in air glow discharges at currents of approximately 10 mA is close to 2000 K.[4]

In order to take this elevated gas temperature into account, it was assumed that $\mu_e p$ depends linearly on T:

$$(\mu_e p)_T=T/T_0(\mu_e p)_{T_0}. \tag{3}$$

Assuming that the electric field in the discharge is given as the anode voltage divided by the gap distance, and that the current density at midplane is the current divided by the cross section of the discharge at this plane, the electron density at this position can be estimated. The cross section of the discharge was obtained from Fig. 2, by considering the radius, where the intensity decreased to half of the maximum intensity, as the effective discharge radius. For $p=760$ Torr, $j=3.8$ A/cm^2 and $E=1.2$ kV/cm, and $T=2000$ K, the estimated electron density at midplane is 5×10^{12} cm^{-3}.

In air, the main electron-loss process is electron attachment to oxygen. The energy density required to sustain a discharge in such an attaching gas is given as

$$P=n_e W_{\mathrm{ion}}/\tau, \tag{4}$$

where n_e is the electron density, W_{ion} the effective ionization energy, and τ is the average lifetime of the electrons. At concentrations of 10^{13} cm^{-3}, in atmospheric air, τ is 10 ns.[6] Assuming that the effective ionization energy is 50 eV, the power density required for the sustainment of an atmospheric air plasma with electron densities of 5×10^{12} cm^{-3} is 4 kW/cm^3. Assuming that the average electric field in the glow is 1.2 kV/cm, and the current density at midpoint between the electrodes is approximately 3.8 A/cm^2, the experimentally obtained power density is 4.6 kW/cm^3, a value which is close to the theoretical value.

Although the plasma volume in this experiment is still only cubic millimeters, the described method allows us to scale it up to larger values. In the longitudinal direction this can be achieved by extending the electrode gap, which requires increasing the applied voltage. In the transverse direction large volume plasma operation can be achieved by superimposing microhollow cathode discharge supported glows through parallel operation.[7] The possible individual control of each of the discharge elements permits us to generate any desired plasma pattern in the transverse plane. A limiting factor is the power density, which at this point would prevent us from generating large volume plasmas. However, experimental results with combustion-assisted glow discharges in air indicate that the power can be reduced by orders of magnitude.[8] Experiments with combustible additives and additives with low ionization potential are underway.

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