1996

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Original Publication Citation

Schoenbach, K. H., Verhappen, R., Tessnow, T., Peterkin, F. E., & Byszewski, W. W. (1996). Microhollow cathode discharges. *Applied Physics Letters, 68*(1), 13-15. doi:10.1063/1.116739

Microhollow cathode discharges

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(Received 25 September 1995; accepted for publication 6 November 1995)

The current–voltage characteristics of hollow cathode discharges and their predischarges in argon under dc and pulsed conditions were found to have a positive slope at pressures up to approximately 50 Torr, and currents up to 20 mA, at a hole diameter of 0.7 mm. In this range of pressure and current, parallel operation of hollow cathode discharges, without ballast, was demonstrated. Scaling to higher pressure is possible by reducing the hole diameter. Pulsed experiments with an array of cathode rings of 75 μm diameter allowed us to obtain parallel operation of more than 50 discharges at a pressure of 350 Torr in air. © *1996 American Institute of Physics.* [S0003-6951(96)04001-8]

The current density in hollow cathode discharges exceeds that of linear discharges by orders of magnitude for comparable discharge voltages. The main mechanism responsible for this current enhancement is assumed to be the "Pendel" effect,[1] the oscillatory motion of electrons between the opposite cathode fall regions of the hollow cathode, an effect which causes a drastic increase in the number of ionization processes.

The lower limit in pressure for this effect to occur is according to Helm[2] determined by the loss of "Pendel" electrons, which reach the opposite cathode wall and are removed from the discharge. This condition leads to an expression for the minimum value of gas pressure p times cathode hole diameter D for which the hollow cathode discharge can be sustained:[2]

$$pD = \ln f^{-1}/(\langle\sigma\rangle n_0), \tag{1}$$

with n_0 being the gas density at a pressure of 1 Torr, and f a loss factor. The average collision cross section $\langle\sigma\rangle$ is defined as the integral of the energy dependent elastic and inelastic cross sections over the electron accelerating cathode fall, the negative glow, and the electron decelerating cathode fall at the opposite cathode wall, divided by the cathode hole diameter. For argon the average cross section was measured as 5.5×10^{-16} cm^2, about twice the value of the maximum cross section for ionization (3.2×10^{-16} cm^2).

Comparison of Eq. (1) with experimental results[3] for the critical pressure and hole diameter at which the hollow cathode discharge can be sustained, showed that the critical loss factor is approximately 0.6 for helium, neon, and argon as fill gases, for cathode holes with dimensions on the order of 2 cm. Accordingly, for argon the minimum or critical value of pD is 0.026 Torr cm. The upper value of hollow cathode discharge operation is at a pD on the order of 10 Torr cm.[4]

Typically hollow cathode discharges are operated at sub-Torr pressures and cathode diameters in the centimeter range. Experiments at higher pressures ($p>25$ Torr) in noble gases have been performed by Sturges and Oskam[5] with parallel cathode plates down to millimeter distance. Hollow cathode discharges at pressures up to 100 Torr in neon in cylindrical and spherical holes, respectively, of 0.75 mm diameter have been studied by White,[6] at values of pD close to the upper limit. The measured current–voltage characteristics for a 100 Torr neon discharge at $pD=7.5$ Torr cm in a molybdenum hollow cathode showed a shallow, but well-defined falling characteristics extending to 18 mA, except for the current range where the discharge transfers from the face of the cavity to the interior.

Whereas White has concentrated on the upper pD range for submillimeter cylindricals hollow cathode discharges, we have explored the discharge characteristics of these microhollow cathode discharges in a range of pD close to the lower limit for the onset of the "Pendel" effect. The cross section of the hollow electrode geometry is shown in Fig. 1. It consists of a cylindrical hole in molybdenum of 0.7 mm diameter and 2.1 mm depth. The cathode is separated by a 0.25 mm mica spacer from a ring-shaped anode of 2 mm i.d. dc voltages of up to 600 V and pulsed voltages of up to 800 V with 1 ms duration were applied. The measurements were performed in flowing argon. Discharge current and voltage were measured using a current viewing resistor and a high voltage probe, respectively. Also, the discharge was observed end-on, time integrated, by means of a microscope connected to a CCD camera.

Figure 2 shows the dc current–voltage characteristics for pressures of 3.5, 5.0, 7.5, 16.5, and 56 Torr, corresponding to pD values of 0.25, 0.35, 0.53, 1.16, and 3.92 Torr cm over a current range from 0.01 to 400 mA. In addition, for the pres-

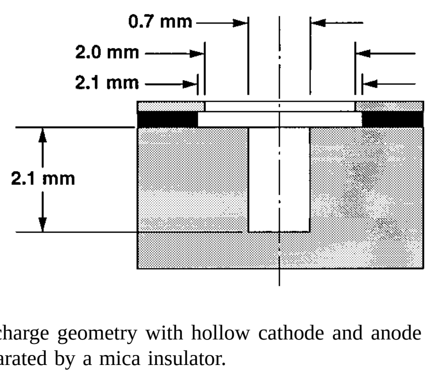

FIG. 1. Discharge geometry with hollow cathode and anode (both molybdenum), separated by a mica insulator.

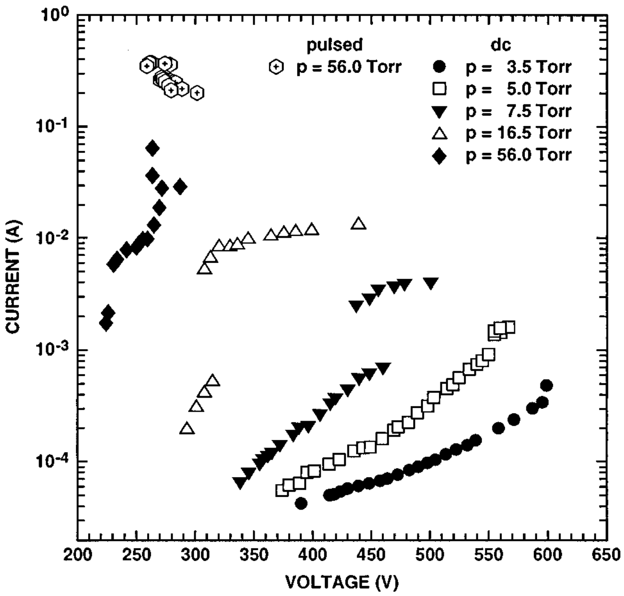

FIG. 2. Current–voltage characteristics of the microhollow cathode discharge in argon.

sure of 56 Torr, the characteristic obtained in the pulsed mode is shown. Except for the lowest pressures the current traces show a distinct discontinuity. It becomes more pronounced and is shifted to lower voltages with increasing pressure and current, respectively.

The visual appearance of the discharges varies depending on gas pressure and current. At lower pressures (<5 Torr), or low current levels, respectively, the boundaries of the plasma column in the cathode hole are rather diffuse. For higher pressures, just below the current discontinuity, a well-defined plasma column on the axis of the hollow cathode is observed with a smaller diameter compared to the hollow cathode diameter; past the transition, the plasma column fills almost the entire cathode hole. Photographs of the discharges in these two modes are shown in Figs. 3(a) and 3(b). Spectral measurements indicate the role of electrode vapor in this transition from a low to a high current mode. The relative intensity of the electrode vapor lines (compared to the gas emission) increases drastically when the discharge transfers into the higher current mode.

The slope of the current–voltage characteristics at pressures below 16.5 Torr is positive over the entire range of observation. At a pressure of 56 Torr, the slope seems to turn negative for currents above 30 mA. For dc operation we were limited to currents of approximately 35 mA due to excessive Joule heating. In the pulsed mode, however, we were able to extend the current range to almost 500 mA. In this mode the change from positive to negative differential conductivity is for the pressure of 56 Torr clearly visible (Fig. 2). This negative slope at *pD*'s considerably above the critical value is consistent with results obtained by White.[6]

The fact that the current–voltage characteristics of low *pD* hollow cathode discharges have a positive slope over a wide range of currents allows us to place them in parallel without using ballast resistors for the single discharges. This was demonstrated by using a set of four holes in molybde-

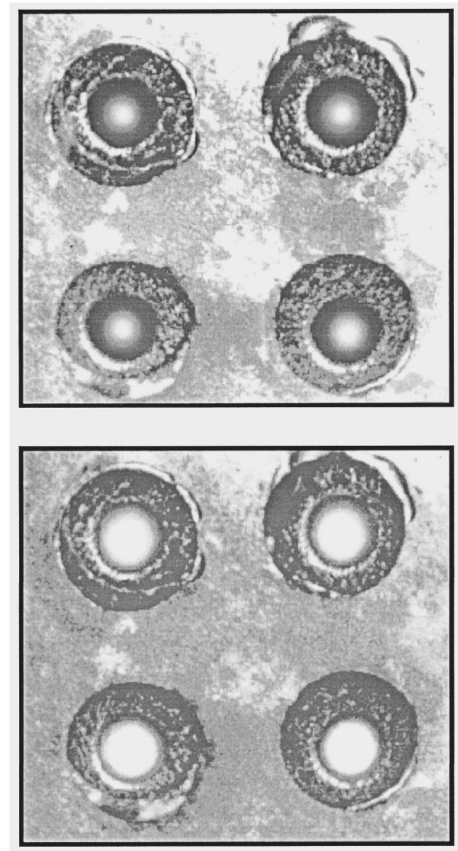

FIG. 3. Array of hollow cathode discharges in argon at a pressure of 16.5 Torr in the "predischarge" mode (above) and the hollow cathode discharge mode (below).

num with the same diameter as before. The discharges in the low current mode [Fig. 3(a)], as well as in the high current mode [Fig. 3(b)] are not affecting each other, as expected. The distance between the holes which in this case was large compared to the hole diameter, can be reduced to fractions of the hole diameter without affecting the discharge array. A system with approximately 50 cathode openings of 200 μm, separated by 10 μm, provided a stable array of hollow cathode discharges in air at 50 Torr. By reducing the cathode openings to values of 75 μm it was possible to increase the pressure (of air) to 350 Torr. It is expected that further reduction of the hole diameter will allow us to generate arrays of hollow cathode discharges in atmospheric air.

Discharges operated below the current discontinuity are Towsend discharges along a path from the interior of the cathode hole to the backside of the hollow anode. In this mode electrons may obtain energies close to value determined by the applied voltage and form axial electron beams. For discharges operated above the current continuity, these Townsend discharges or "predischarges" constitute the initial stage in their temporal development.[7] The predischarge generates a virtual anode close to the anode which propagates toward the cathode orifice.[8] This modifies the initially dominantly axial electric field at the orifice of the hollow cathode and generates a more radial field structure. The change in electric field favors the onset of the Pendel effect, which generates a highly ionized plasma column on the axis of the hollow cathode. The discharge mode above the current discontinuity therefore constitutes the real hollow cathode discharge. The lowest *pD* value for which this hollow cathode discharge can be sustained in our discharge configuration, for voltages below 600 V, is 0.53 Torr cm (p=7.5 Torr), 20 times the value obtained with Eq. (1).

Modeling of a hollow cathode discharge in argon has provided current–voltage characteristics similar to the ones, which we have obtained experimentally in the lower *pD* range, except for the transition region from predischarge to hollow cathode discharge.[9] Whereas our measurements show only a slight, if any reduction in forward voltage when the discharge enters the hollow cathode mode, in the computed current–voltage characteristics this transition is accompanied by a considerable drop of the discharge voltage. The (relatively slight) increase in current with voltage above the transition into the hollow cathode mode, which is seen in both the modeling and experimental curves (Fig. 2), is attributed to the fact that the plasma sheath in the hollow cathode mode covers the entire hollow cathode surface, and any increase in current requires an increase in cathode fall voltage.[9]

The electron energy distribution in the hollow cathode discharge mode contains electrons with an energy corresponding to the cathode fall.[10] Electrons with at least 100 eV were measured in the negative glow of a parallel plate hollow cathode discharge.[11] The increased ion flux to the cathode in the hollow cathode mode causes an increase in the concentration of sputtered electrode material and explains the observed occurrence of metal spectral lines in this discharge phase. Eventually heating of the cathode causes thermionic electron emission to become the dominant effect rather than electron emission through ion impact, and the voltage across the discharge drops to values of less than 20 V. In recent experiments with dispenser material (tungsten impregnated with barium oxide) as cathode material we have demonstrated this transition to the thermionic mode at currents of approximately 100 mA for a 0.75 mm diameter hollow cathode.

The possibility to generate arrays of microhollow cathode discharges without using ballast suggests their use as simple flat panels in light sources at high pressures. The discharges can be operated in two stable modes: in the ''predischarge'' or electron-beam mode or as fully developed hollow cathode discharges. Other applications are large area electron and ion sources and, because of the nonthermal electron energy distribution, particularly in the electron-beam mode, as gas processing devices.

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