Effect of limiting the cathode surface on direct current microhollow cathode discharge in helium

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Title	**Effect of limiting the cathode surface on direct current microhollow cathode discharge in helium**
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Abstract	This paper describes how to light several microdischarges in parallel without having to individually ballast each one. The V-I curve of a microhollow cathode discharge is characterized by a constant voltage in the normal glow regime because the plasma is able to spread over the cathode surface area to provide the additional secondary electrons needed. If one limits the cathode surface area, the V-I characteristic can be forced into an abnormal glow regime in which the operating voltage must increase with the current. It is then possible to light several microdischarges mounted in parallel without ballasting them individually.

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1. Introduction

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5 Microdischarges are nonequilibrium discharges spatially confined to dimensions smaller than 1 mm. They are a promising approach to

6 the generation and maintenance of stable dc glow discharges at atmospheric pressure and they present interesting challenges for

7 plasma science (impact of quantum electrodynamics on spontaneous emission rate and quasineutrality breaking).1 Parallel

8 microplasmas can be created using several kinds of microdevices.2 Some teams use ballasts to individually initiate the plasma in each

9 microcavity independently.3,4

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11 The aim of this work is to investigate and optimize the ignition of parallel microdischarges without individual ballasts to create an array.

12 This area can be extended by the way of a third plane electrode5,6 or a nozzle electrode.7 The microhollow cathode (MHC) used in this

13 experiment is a $Ni:Al_2O_3:Ni$ sandwich structure having one or several holes of 250 m in diameter. The dielectric layer (Al_2O_3) has a

14 thickness as high as 250 μm whereas the nickel electrode thickness is only 6 μm. Ni is deposited by electrodeposition process. The holes

15 are made by laser drilling.

2. Experimental setup

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18 The MHC is installed inside a vacuum chamber linked to a primary pump. The discharge can operate in a range of pressures from 100 to

19 1000 Torr. Experiments were carried out in He. A 0–2500 V dc (300 W) power supply is used to operate the microdischarges. Electrical

20 measurements are performed using a Tektronix oscilloscope and high voltage probes. The discharge voltage is measured between input

21 and output resistances (R_1=19 kOhm, 16 W and R_2=1 kOhm) and the discharge current through R_2 is connected to the ground. An imaging

22 system including an intensified charge coupled device (ICCD) camera (512*512 Princeton Instruments) and an optical system for

23 magnification was installed in front of the microcavity.

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3. Results & Discussion

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30 V-I curves for a single hole microdevice for four pressures are presented in Fig. 1. These characteristics were obtained by measuring the

31 current during linear increase and decrease in supply voltage (40 s period). Up until now, experiments carried out by other teams[8–11]

32 with the same MHC configuration have shown the existence of an abnormal glow regime for small values of the discharge current.[12]

33 The effect of the cathode thickness has been predicted by a model[12] based on solutions of fluid equations in the drift-diffusion

34 approximation for the electron and ion transport coupled with Poisson's equation. If the discharge is sustained by electron emission

35 from the outer surface of the cathode (case corresponding to a thin cathode at low current), the V-I curve has a negative slope before

36 showing a constant voltage versus current. If the discharge is sustained by electron emission from inside the hollow cathode (case

37 corresponding to a thick cathode at low current), the V-I curve has a positive slope, which corresponds to the abnormal glow regime. In

38 our case, the cathode thickness being very small, we observe a slight decrease in the voltage at a very low current as predicted by the

39 model[12] (only for decreasing values of supply voltage) before the normal glow regime (inset of Fig. 1). Other teams usually use much

40 thicker cathodes (about 100 µm).[8–11] As a consequence, they have observed a positive V-I slope at a low current in good agreement

41 with the same model. The breakdown voltage values have a Paschen law behavior as also observed by other teams.[9]

42

43 After breakdown, we observed a self-pulsing regime of the microdischarge, which was studied in detail by Rousseau and Aubert.[10]

44 During increasing current, the discharge is no longer confined inside the cavity. It extends to the outer cathode surface to cover a large

45 area. Thus, electron and ion production is increased by sheath expansion. We obtain a roughly constant discharge voltage resulting from

46 the equilibrium between the size of the discharge spread and the value of the discharge current. This is the normal glow regime. As part

47 of decreasing the supply voltage, a hysteresis is observed in the transition between the breakdown potential and the normal glow

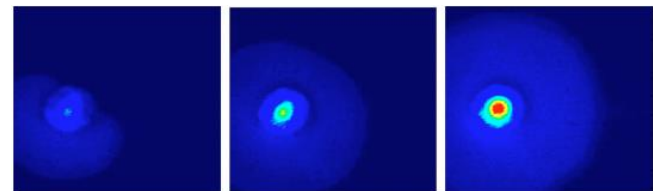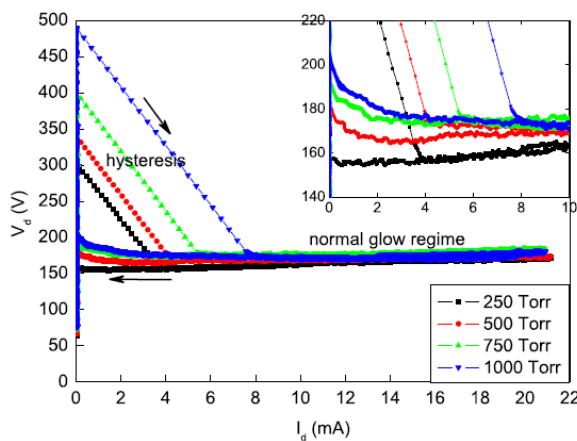48 regime as seen in a typical dc discharge at low pressure.[13]

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FIG. 2. Microdischarge spread on the cathode surface for discharge currents of 5.5, 10.3, and 19.3 mA, 750 Torr, He.

FIG. 1. V-I curves of a 250 µm single hole MHC device in helium. (Inset) Zoom of the curves at low current.

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51 The big difference between the breakdown voltage and the operating voltage can be an issue to operate a multiple hole device without

52 ballasting each of the microdischarges individually. Indeed, in this case, once a first hole has ignited, the voltage between the anode

53 and cathode drops to a lower value well below the breakdown potential, which therefore makes the second cavity hard to breakdown

54 independently. However, by increasing the discharge current in the normal glow regime, the microdischarge spreads out of its cavity,

55 as shown by the optical emission intensity in Fig. 2, and can potentially initiate microdischarges in the nearest holes. However, in our

56 experiment, nearest cavities do not necessarily initiate in priority. Another parameter influences the ignition of some holes. Due to the

57 laser drilling process, holes are not exactly all the same at the microscopic scale. Some of them have a more or less rough edge which

58 can facilitate their ignition.

59

60 According to previous works,4,14,15 microdischarge arrays only operate in the abnormal glow regime. In the present simply fabricated

61 MHC devices, we do not obtain this regime even at quite high currents (20 mA). We propose to spatially limit the area of the cathode

62 by a dielectric layer while keeping the same MHC configuration. For this purpose, we covered the cathode surface with a 50 μm thick

63 layer of Kapton. We made a controlled circular opening through this layer in order to expose a small part of the cathode surface to ion

64 bombardment. The circular opening around the 250 m diameter cavity was approximately 600 m in diameter. The resulting V-I curves

65 for 250 and 750 Torr are shown in Fig. 3. We obtained about the same breakdown voltages as in the case without limiting the cathode

66 surface. However, the discharge voltage V_d now increases with the current showing a positive differential resistance similar to the

67 abnormal glow of low pressure plasmas.13 Moreover, an anticlockwise hysteresis is superposed to this abnormal glow regime.

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69 We expect that energetic ion bombardment occurs only on the exposed cathode surface. Consequently, the amount of discharge spread

70 can be limited by adjusting the dimension of the dielectric opening. Tests were carried out on the same single hole microdevice at

71 atmospheric pressure for cathode opening diameters between 500 and 2500 μm. V-I curves corresponding to this study are presented

72 in Fig. 4. The V-I curve for the smallest opening has the most pronounced slope. The reason is attributed to the limited plasma expansion.

73 Since the emission of secondary electrons cannot be increased by plasma expansion, Id can only be increased by an increase in the

74 cathode fall. In contrast, for the largest opening, the microdischarge can expand. Since the cathode expansion is not limited the cathode

75 fall voltage does not need to increase and the discharge voltage remains approximately constant, as observed in Fig. 4 for a 2500 m

76 opening. To summarize, the smaller the exposed cathode surface, the more pronounced the abnormal glow regime.
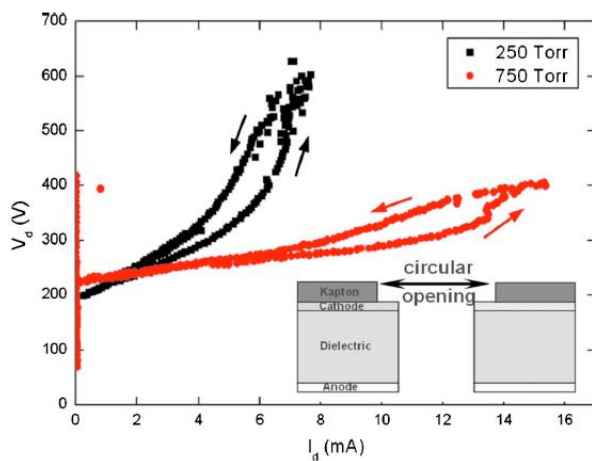

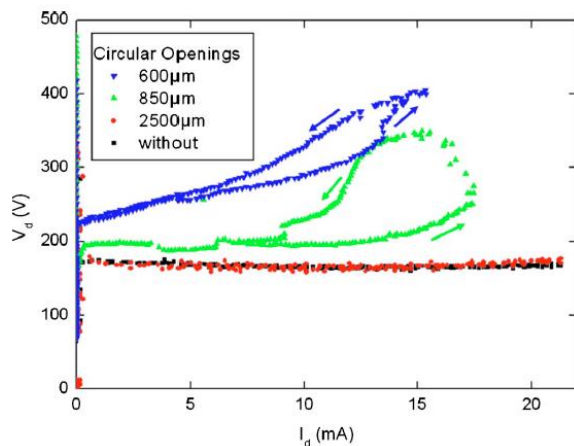FIG. 3. V-I curves for a single hole MHC with the cathode area limited 600*600 μm² at 250 and 750 Torr.

FIG. 4. V-I curves for a single hole MHC at 750 Torr for several cathode areas.

77 Let us now consider the case of a microdevice with seven holes in a line, separated center to center by a distance of 260 μm. If one does

78 not limit the cathode, the ignition of this microdevice always begins by the ignition of a first and single microcavity for small values of

79 the discharge current (<1 mA). When increasing I_d, the first microdischarge spreads on the cathode surface.16 The spread can overlap

80 to other holes but does not always induce their ignition. In our case, only the first hole ever ignited, as illustrated in the left inset of Fig.

81 5, even for large discharge currents (25 mA).

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83   By covering the cathode surface with a dielectric layer, we limited the cathode area to 600*2700 µm². Note that no dielectric separates

84   the seven holes. While the corresponding V-I characteristic had a larger breakdown potential (245 V) than before (185 V), it still

85   corresponded to the ignition of the first hole. Then, for increasing discharge currents, the V-I curve shown in Fig. 5 has a positive

86   differential resistance, corresponding to an abnormal glow regime. By limiting the cathode surface, we were able to ignite the other

87   cavities at 27 mA without having to ballast them individually.

88

89   This curve is also characterized by small jumps in V_d, with amplitudes around 5 V at 9, 13, and 19 mA. According to the ICCD pictures,

90   each jump corresponds to the ignition of an additional cavity. As the three jumps mentioned above appear below 245 V, these cavities

91   were ignited at voltages lower than the initial breakdown potential (above 185 V). In the inset of Fig. 5 (cathode limited), we can observe

92   that the emission of each hole is not the same, indicating that the current is not equally shared between the cavities. Once multiple

93   holes are ignited, the system is then at a point of having less current in each cavity but more overall. As a consequence, V_d is reduced.
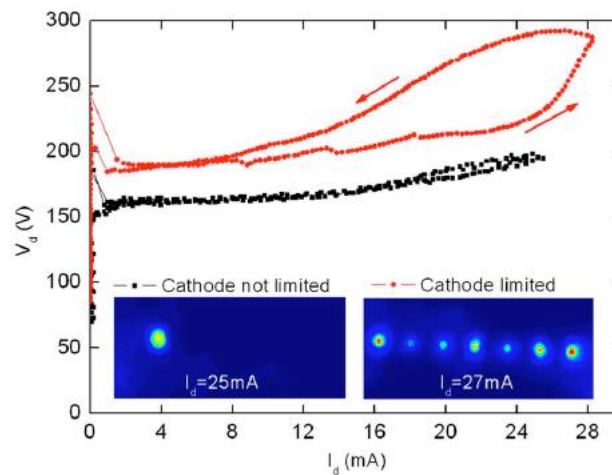
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95

96   **FIG. 5. V-I curve at 750 Torr for seven holes in line microdevice with/without cathode surface limited.**

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98   It would be natural to assume that once a first discharge is initiated, the breakdown potential for adjacent holes is lowered due to the

99   seed electrons provided by the first plasma. However, there is a problem with this assumption. While these electrons could assist the

100 ignition of an additional microdischarge, it should favor adjacent holes over further removed holes. One can clearly see in the inset

101 picture that this is not the case. The four brightest holes are not adjacent and the ICCD pictures clearly show that it is not just the

102 adjacent holes that ignite. Again, this effect is probably due to the fact that ignition is also influenced by the micrometric geometry of

103 the electrodes, which are not exactly the same from a hole to another.

104

105 The hysteresis we observed in the cathode limited case seems to be due to the heating of the microdevice. Indeed, in our experiments,

106 the period of the power supply voltage lasts by 40 s. By significantly reducing this period to less than 1 s, the hysteresis became much

107 weaker. Long life helium metastables might also play a role in the hysteresis phenomenon; this hypothesis would need a dedicated

108 study.

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110

4. Conclusion

As a conclusion, we obtain an abnormal glow regime for high values of discharge current by limiting the outer cathode surface with a dielectric layer. The smallest cathode surface exposed to ion bombardment is required to get the most significant abnormal glow regime. This property is very helpful to initiate microdischarge arrays without individual ballasts.

5. References

[1] R. Foest, M. Schmidt, and K. Becker, Int. J. Mass. Spectrom. 248, 87 (2006).

[2] K. H. Becker, K. H. Schoenbach, and J. G. Eden, J. Phys. D 39, R55 (2006).

[3] P. von Allmen, D. J. Sadler, C. Jensen, N. P. Ostrom, S. T. McCain, B. A. Vojak, and J. G. Eden, Appl. Phys. Lett. 82, 4447 (2003).

[4] P. von Allmen, S. T. McCain, N. P. Ostrom, B. A. Jovak, J. G. Eden, F. Zenhausern, C. Jensen, and M. Oliver, Appl. Phys. Lett. 82, 2562 (2003).

[5] R. H. Stark and K. H. Schoenbach, Appl. Phys. Lett. 74, 3770 (1999).

[6] A.-A. H. Mohamed, R. Block, and K. H. Schoenbach, IEEE Trans. Plasma Sci. 30, 182 (2002).

[7] T. Yokoyama, S. Hamada, S. Ibuka, K. Yasuoka, and S. Ishii, J. Phys. D 38, 1684 (2005).

[8] S.-J. Park, K. S. Kim, and J. G. Eden, Appl. Phys. Lett. 86, 221501 (2005).

[9] X. Aubert, G. Bauville, J. Guillon, B. Lacour, V. Puech, and A. Rousseau, Plasma Sources Sci. Technol. 16, 23 (2007).

[10] A. Rousseau and X. Aubert, J. Phys. D 39, 1619 (2006).

[11] S.-J. Park, J. G. Eden, J. Chen, and C. Liu, Appl. Phys. Lett. 85, 4869 (2004).

[12] J. P. Boeuf, L. C. Pitchford, and K. H. Schoenbach, Appl. Phys. Lett. 86, 071501 (2005).

[13] M. A. Lieberman and A. J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, 2nd ed. (Wiley, Hoboken, NJ, 2005), pp. 538– 539.

[14] S.-J. Park, J. Chen, C. Liu, and J. G. Eden, Electron. Lett. 37, 171 (2001).

[15] J. Chen, S.-J. Park, J. G. Eden, and C. Liu, J. Microelectromech. Syst. 11, 536 (2002).

[16] T. Dufour, R. Dussart, M. Mandra, and L. J. Overzet, 18th International Symposium on Plasma Chemistry, ISPC, 2007 (unpublished).