한국표면공학회지
Journal of the Korean Institute of Surface Engineering
Vol. 34, No. 5, Oct. 2001
<연구논문>

Atmospheric Pressure Micro Plasma Sources

Ian Brown*

Lawrence Berkeley National Laboratory Berkeley, California 94720, USA

Abstract

The hollow cathode discharge is a kind of plasma formation scheme in which plasma is formed inside a hollow structure, the cathode, with current to a nearby anode of arbitrary shape. In this scheme, electrons reflex radially within the hollow cathode, establishing an efficient ionization mechanism for gas within the cavity. An existence condition for the hollow cathode effect is that the electron mean-free-path for ionization is of the order of the cavity radius. Thus the size of this kind of plasma source must decrease as the gas pressure is increased. In fact, the hollow cathode effect can occur even at atmospheric pressure for cathode diameters of order 10-100 μm. That is, the "natural" operating pressure regime for a "micro hollow cathode discharge" is atmospheric pressure. This kind of plasma source has been the subject of increasing research activity in recent years. A number of geometric variants have been explored, and operational requirements and typical plasma parameters have been determined. Large arrays of individual tiny sources can be used to form large-area, atmospheric-pressure plasma sources. The simplicity of the method and the capability of operation without the need for the usual vacuum system and its associated limitations, provide a highly attractive option for new approaches to many different kinds of plasma applications, including plasma surface modification technologies. Here we review the background work that has been carried out in this new research field.

1. Introduction

Hollow cathode plasma sources have been known for many years, and their properties and behavior have been explored and reported in the literature; see for example[1-4]. Some of the typical forms that the hollow cathode configuration can take are shown in Figure 1. A fundamental characteristic of this type of plasma source is that a column of plasma forms within the cathode cavity at a potential greater than the cathode itself (close to the anode potential), forming a potential well for electrons within the hollow cathode and allowing electrons to reflex (oscillate back and forth) radially. If the electron mean-free-path for ionizing collisions with neutral gas atoms is in the right regime, a single electron can cause many ionizations and a relatively high density plasma can be efficiently maintained.

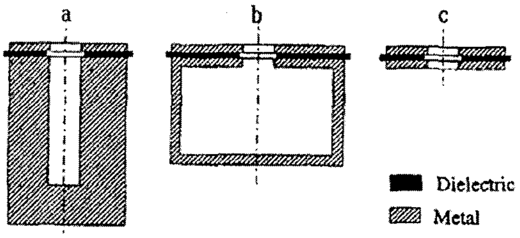

Fig. 1 Some typical hollow cathode discharge plasma source configurations.

In recent years, hollow cathode plasma sources have been investigated at higher gas pressure regimes and accompanying smaller cathode sizes. Pivotal in this novel direction of exploration has been the work of Schoenbach and coworkers, who have reported in a series of publications in the past several years on their work with "micro hollow cathode discharges" (MHCD) at pressures as high as, and even exceeding, atmospheric pressure[5-10]. Atmospheric pressure MHCD plasma sources are of startlingly simple construction, with characteristic dimensions in the range of about 100 μm. Typical voltage drop across the source (anode-to-cathode applied dc voltage) is several hundred volts, and dc current drawn is typically in the range 0.1 to a few tens of milliamperes. Plasma electron density within the source cavity can be up to about 10^{15} cm^{-3}. Schoenbach's group[8-10] and other workers[11] have also developed variants of the basic MHCD concept in which plasma is also formed at some distance away from the MHCD cavity. That is, a somewhat-extended plasma is created that can be used for an application that lies some short distance away from the MHCD source itself.

We present here a brief review of the present status of this new research area. Following a description of typical MHCD source construction and electrical features, the operational and plasma performance parameters are outlined. Recent developments in some alternative approaches to micro plasma source design are also discussed.

2. Description of the MHCD Plasma Source

In principle it would be possible to make a micro hollow cathode plasma source by miniaturizing any of the geometric shapes that have been demonstrated to work at macroscopic size.

However, for simplification of the micro-source manufacturing process one particular source configuration has evolved to be the preferred design mostly used, as shown in Figure 2.

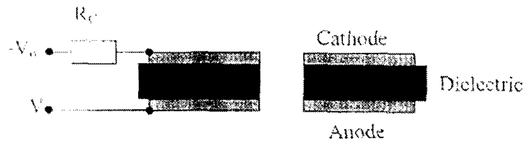

Fig. 2 Schematic of the micro hollow cathode discharge configuration.

A sandwich of metal-insulator-metal is constructed. The insulator is about 250 μm thick, and may be made of alumina (Al_2O_3) or mica, or kapton (high temperature polymer), or other material. The metal is about 100 μm thick and may be made of molybdenum or tungsten or copper, or other material. A hole of diameter about 100 μm is drilled completely through the 3-layer sandwich, and wires are attached to the two metal electrodes so that voltage can be applied.

In our own MHCD test version, each small MHCD plasma source was made from a 2.5 cm (1 inch) square piece of 250 μm kapton foil, with copper metalization in the form of a 1 cm square on either side applied using printed circuit board techniques. Wires were soldered to each copper electrode to allow voltage to be applied. The configuration is initially completely symmetric and there is no distinction between cathode and anode until the electrical circuitry is defined. The source performance is controlled by the discharge current, which in turn is conveniently controlled by a series resistor. Thus the electrical circuit is simply an external d.c. power supply (voltage variable up to 1.5 or 2 kV, with current capability up to several tens of milliamperes) with a current-limiting series resistor of perhaps 100 kΩ.

Operation of the source is simplicity itself - the power supply is switched on, with the source located (safely) in atmospheric pressure air. No special conditions of any kind are required. Discharge current is controlled by the power supply voltage and the series resistor. Source lifetime may be limited at higher power, depending on the kind of insulator material used. The MHCD plasma can be pulsed by means of a switched power supply, with consequent reduction in mean power and in source thermal handling requirements by a factor equal to the duty cycle employed.

3. Performance of the MHCD

3. 1 Existence condition

Hollow cathode discharges have been divided into three separate regimes of operation[5, 6, 12], corresponding to different discharge currents, different parts of the discharge current-voltage characteristic (see below), and different visual appearances of the discharge plasma. In the low current regime, a simple glow discharge occurs between cathode and anode. The second regime entails a true "hollow cathode effect" in which electrons within the hollow cathode oscillate radially, or "reflex", in the potential well formed by the cathode itself and a central plasma column that transfers the anode potential into the cathode cavity. Reflexing electrons can cause ionizing collisions many times over, and hence provide a highly efficient ionization mechanism. A condition for this to occur is that the electron mean-free-path be not too much smaller than nor greater than the hollow cathode radial dimension. This condition for the existence of the hollow cathode effect can be quantified[5, 13] as

$$0.1 \leq pD \leq 10 \text{ (Torr.cm)} \qquad (1)$$

where p is the gas pressure and D is the cathode diameter, and it is understood that the specified range is approximate only. It follows from Eq. (1) that atmospheric pressure hollow cathode discharges can occur when the cathode diameter is of order 100 μm or less, as indeed is observed experimentally.

3. 2 Voltage-current characteristics

The atmospheric pressure MHCD plasma source operates at a cathode-to-anode voltage drop typically in the range 200 - 400 V and a current typically in the range 0.5 - 50 mA. An idealized I-V characteristic typifying the operation of the kind of source described here is shown in Figure 3. The three regimes of operation referred to above can be readily distinguished in the shape of the I-V curve. Although all three regimes refer to plasma that exists in a hollow cathode geometry, in a strict sense it is only in the middle regime that reflexing electrons dominate the plasma formation process - the hollow cathode effect.

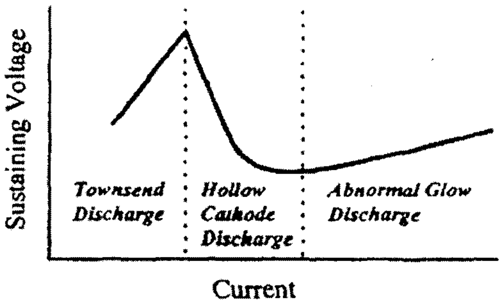

Fig. 3 Idealized current-voltage characteristic of atmospheric pressure MHCD in air; (from[9]).

3. 3 Plasma parameters

The ion density and electron temperature within the MHCD plasma have been measured spectroscopically. For typical operational parameters (about 10 mA discharge current) the peak plasma density is typically of order 10^{15} cm^{-3}, a surprisingly high value, and the electron temperature is of order 1 eV.

4. Source Variants

4. 1 Three-electrode systems

In its basic form the MHCD plasma is contained almost completely within the cathode cavity, while for many (but not all) applications one requires that plasma also exist some short distance away from the region in which it is formed so as to be available, for example for surface modification. To this end, a number of source variants have been explored in which an additional electrode is employed as a means for inducing the plasma to extend some distance from the MHCD itself. Several such configurations are shown in Figure 4. Depending on the electrode biasing, the I-V characteristic can change significantly, and this can also used to advantage for parallel source operation (see below).

The configuration used by Schoenbach[8] is shown in Figure 5. A third electrode is positioned at a distance of up to 10 mm from the anode of the MHCD and biased positively at some several hundred up to several thousand volts with respect to the MHCD anode (which is at ground potential). The MHCD can be viewed, in this context, as a source of electrons that are extracted from the MHCD cavity and used to support a d.c. glow discharge in the intervening space. The external plasma so formed is of diameter several times that of the MHCD diameter, and the on-axis electron density at midplane is of order 10^{13} cm^{-3}.

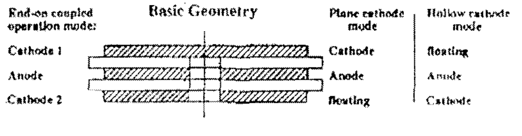

Fig. 4 Three-electrode systems that have been explored for forming plasma that extends some distance out of the basic MHCD cavity itself; (from[11]).

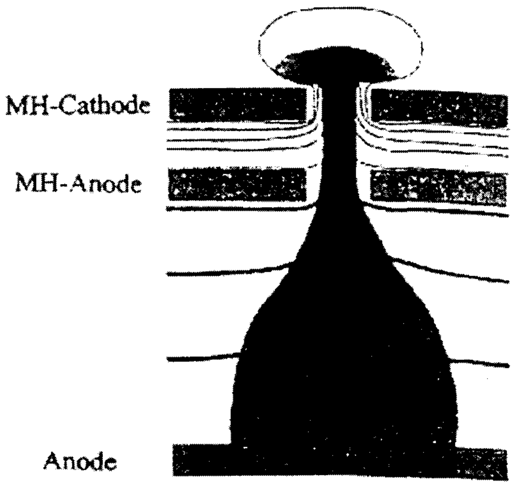

Fig. 5 Three-electrode micro-plasma configuration used by Schoenbach to produce plasma at a distance of up to 1 centimeter from the MHCD; (from[9]).

4. 2 Parallel operation of large arrays

Most plasma applications, and virtually all surface-modification applications, call for a plasma of macroscopic dimensions. This can be accomplished of the tiny MHCD plasma by making a large number of such sources all operating in parallel. The simplicity of the source eases the manufacturing job, and the problem one is left with is the plasma/electrical concern of whether or not multiple sources will all stay alight simultaneously. It can be taken as a general theorem that devices with a positive I-V slope (positive differential conductivity; i.e., resistive in nature) can be operated in parallel without any special concerns, whereas devices with a negative I-V slope (negative differential conductivity (decreasing current for increasing voltage) cannot be so operated. In the latter case, individual "ballast" (series) resistors need to be added to each source so as to provide isolation between the separate sources. Referring to the idealized MHCD characteristic shown in Figure 3, we see that the MHCD shows a positive I-V slope in the low current regime (Townsend discharge) and in the high current regime (abnormal glow discharge), while the slope of the characteristic is negative in the formal hollow cathode mode of operation (reflexing electrons). We thus expect that parallel arrays of MHCD devices should be able to be operated in parallel without individual ballasting in the low current and high current regimes, whereas individual ballasting would be required in the hollow cathode mode. Precisely this behavior was observed by Schoenbach[5].

The conventional way of operating sources in parallel is to add an appropriate series resistor to each source, providing isolation between individual sources by ensuring that the voltage across a source is not dropped by operation of another source. The series resistance can be added in the form of an ordinary resistor, or by fabricating part of the electrode structure from an inherently resistiv material such as doped silicon. The latter approach has been demonstrated by Schoenbach et al[14], who have demonstrated parallel operation of an array of 16 MHCD sources using 1200 ohm-cm Si to provide source ballasting; see Figure 6.

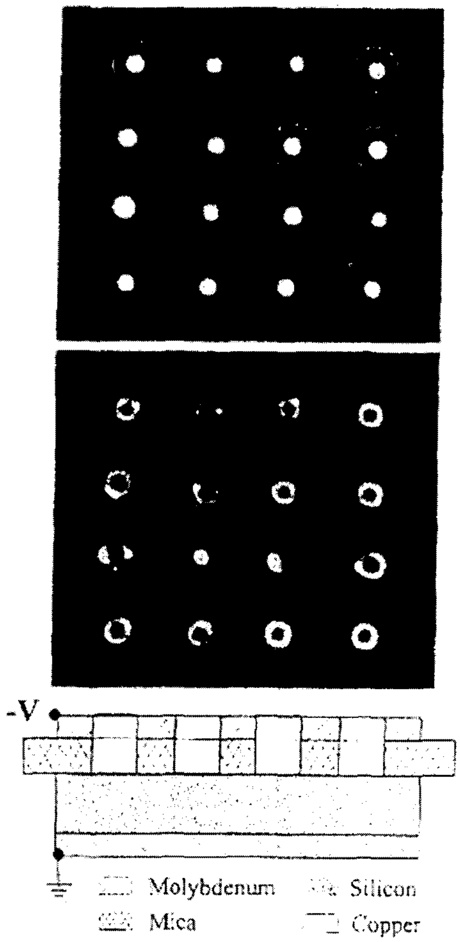

Fig. 6 Multi-source array employing resistive silicon to provide isolation between individual sources; (from[14]).

We point out that Biborosch and coworkers have shown[11] that a 3-electrode system can change the form of the I-V characteristic significantly, causing the I-V slope to be positive where it would otherwise be negative in the basic 2-electrode MHCD configuration. These sources might be able to be operated in parallel without individual source ballasting. This remains to be tested experimentally.

For discharge voltage in the range 200 - 400 V and current in the range 1 - 10 mA, the power dissipated in each source is of order 1 W. If sources are positioned on a square matrix with centers, say, 2 mm apart (an arbitrary value for the sake of example), the power density is ~25 W/cm^2 or ~250 kW/m^2. On the other hand, an array of 10,000 sources forming a rectangular plasma sheet 1 m by 4 cm would dissipate 10 kW. Note that for some applications it may well be feasible, or even preferred, to operate the MHCD sources in a low duty-cycle repetitively-pulsed mode; then the mean power dissipation and thermal load could be reduced substantially.

5. Summary and Conclusion

The micro hollow cathode discharge is a new kind of plasma source that provides a very simple and straightforward means for forming plasma in air at atmospheric pressure. The device is tiny, of typical dimension 100 μm, and dissipates a power of order 1 Watt. Variants of the basic configuration are evolving by means of which plasma can be formed at a distance from the source, allowing use of the plasma for an application at some small distance away from the source itself. Parallel operation of the micro-sources has been demonstrated, providing a means for making large planar arrays of sources in almost arbitrary shape. The sources can be operated in steady-state dc mode or in a repetitively-pulsed mode; there is no particular difficulty associated with source switch-on.

Some of the applications that have been considered to which arrays of atmospheric pressure micro sources could be put include switchable *microwave reflectors/absorbers, environmental* clean-up of various kinds, gas lasers, lighting, and material surface modification. The dual features of atmospheric pressure operation and the ability to shape large planar arrays offer immense versatility and great potential advantage for specific applications.

The field is new and there remains much work to be done to develop this fascinating plasma device to its full potential and to make use of it for new kinds of plasma surface technologies.

References

1. A. D. White, J. Appl. Phys. 30, 711 (1959).
2. D. J. Sturges and H. J. Oskam, J. Appl. Phys. 35, 2887 (1964).
3. V. S. Borodin and Yu. M. Kagan, Sov. Phys. - Tech. Phys. 11, 131 (1966).
4. G. Schaefer and K. H. Schoenbach, in Physics and Applications of Pseudosparks, edited by M. Gundersen and G. Schaefer, (Plenum Press, New York, 1990), p. 55.
5. K. H. Schoenbach, R. Verhappen, T. Tessnow, F. E. Peterkin and W. W. Byszewski, Appl. Phys. Lett. 68, 13 (1996).
6. K. H. Schoenbach, A. El-Habachi, W. Shi and M. Ciocca, Plasma Sources Sci. Technol. 6, 468 (1997).
7. A. El-Habachi and K. H. Schoenbach, Appl. Phys. Lett. 73, 7 (1998).
8. R. H. Stark and K. H. Schoenbach, Appl. Phys. Lett. 74, 3770 (1999).
9. R. H. Stark and K. H. Schoenbach, J. Appl. Phys. 85, 2075 (1999).
10. F. Leipold, R. H. Stark, A. El-Habachi and K. H. Schoenbach, J. Phys. D: Appl. Phys. 33, 2268 (2000).
11. L. D. Biborosch, O. Bilwatsch, S. Ish-Shalom,

E. Dewald, U. Ernst and K. Frank, Appl. Phys. Lett. 75, 3926 (1999).

12. A. Fiala, L. C. Pitchford and J. P. Boeuf, in Proceedings of the 22nd Conf. on Phenomena in Ionized Gases (Hoboken, NJ, 1995), edited by K.H. Becker et al., (Stevens Institute of Technology, Hoboken, NJ, 1995), p. 191.
13. J. W. Gewartowski and H. A. Watson, Principles of Electron Tubes, (Van Nostrand, Princeton, 1965), p. 561.
14. W. Shi, R. H. Stark and K. H. Schoenbach, IEEE Trans. Plasma Sci. 27, 16 (1999).