HOLLOW CATHODE DISCHARGES FOR PLASMA LIGHT SOURCES

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ABSTRACT

Hollow cathode discharges are know to have major advantages over other glow discharges when they are utilized as the plasma sources of such devices as spectral lamps, lasers, and plasma jets. In this work a "wire" hollow cathode discharge device and its operating characteristics such as current/voltage characteristics, and emission spectral are studies. The hollow cathode is constructed from a set of 1 mm in diameter tungsten wires forming a cylinder. Then this structure was enclosed in a cylindrical quartz tube. The plasma chamber was water cooled to obtain stable plasma and also to protect the quartz envelope from excessive heat generated by the plasma. A dc voltage was applied to the electrodes to generate the plasma, and the optical diagnostics were recorded by a spectrometer. The current voltage and optimum operating characteristics of the device were determined. The results of these measurements and findings are discussed in the paper.

INTRODUCTION

Presently, commercial plasma light sources operate based on low-pressure gas discharges. Although, these lamps are known to be efficient compared to others such as incandescent lamps, there is a need to develop more efficient light sources in order to reduce energy consumption currently being used in the daily life. Furthermore, most UV light sources are result of mercury plasma generated by rf power, and their efficiency is in the order of 1% at the UV spectrum . One major application area of the UV light sources is for surface cleaning or surface processing . These UV lamps are generally used for photo-degradation [1] of pollutants on the surfaces by photo-catalysis, or in advanced oxidation processes. For industrial use, large area incoherent UV sources with high photon fluxes are needed. One way to increase efficiency of a plasma source is to utilize energy and charge transfer collision processes efficiently in addition to electron collision excitation. Hollow cathode discharges are known to posses high ion and electron concentrations along with high metastable densities. Therefore, they are major candidates to be utilized as the plasma sources of high efficiency light sources, where energy and charge transfer collision processes along with the electron collision processes can be utilized to produce high intensity of light emission needed for lighting.

In the literature and in commercial use, hollow cathode discharges have found applications as spectral lamps, UV light sources [2] and often considered as a main pumping source for gas lasers [3]. The hollow cathode effect is strongly depended on the cathode geometry, therefore many different form of cathode geometry have also been studies [4].

In this work a "wire" hollow cathode device was designed and operated as a possible plasma source for high-pressure UV light source. In the design, the "pd" constraint, where p is the pressure and d is the gap distance between the electrodes, was used and the device was operated in a wide pressure range from 1 mbar to 100s of mbar. The plasma was generated in this device by a set of thin wires forming the hollow cathode geometry. The design allows to generate the plasma between the individual wires at high pressures and in the volume enclosed by the wires at lower pressures.

HOLLOW CATHODE DISCHARGES

When a planar cathode in a glow discharge replaced by a cathode with some hollow structure, in a specific range of operating pressure, the "negative glow" which has the highest electron density [5] moves inside the hollow structure, and discharge takes place almost entirely inside the hollow cavity. This is known as the hollow cathode effect [6]. Much higher current densities (in some cases up to 10^4 A/cm^2) at relatively love voltages, and much higher emitted light intensities can be achieved in hollow cathode discharges compared to a planar cathode discharges.

One of the main mechanisms contributing to the hollow cathode effect is the pendular electron effect. The electrons emitted from cathode surface inside the hollow cavity are accelerated in the cathode fall region and contribute to further ionization of in the negative glow. Thus hollow cathode discharges posses high ion, metastable, and electron densities. Due to these ionization and excitation processes taking place in the negative glow, the electron density distribution has a definite non-Maxwellian form [7] with a very high density of low-energy electrons, and a significant population of high-energy electrons.

These particular properties of hollow cathode discharges are desirable in applications where high excitation rates, high current densities with low cathode fall, and high electron density to promote the excitation and ionization resulting in high intensity of emitted light. High pressure plasmas used as the light sources would benefit from all the above properties of hollow cathode discharges, since this would translate in high efficiency use of plasmas for light sources.

Furthermore, the mechanisms contributing to the hollow cathode effect are strongly dependent on the operating conditions, the hollow cathode geometry, the nature and pressure of the gas environment in the cavity, the cathode material, and the electrical circuitry. In terms of geometry and pressure, the hollow cathode discharge operation is, in general, restricted to a certain range of "*pd*" where 1 torr-cm < *p*d < 10 torr-cm for rare gases, where p is the operating pressure and d is the diameter of hollow cavity. Due to this *pd* restriction most hollow cathode devices are operated at low pressure, because discharges operating atmospheric pressures require a sub-millimeter or micrometer size hollow cavity geometry. Furthermore, it is desirable to have high densities of species in the plasma to generate light intensity of emitted light. These high densities can be achieved by operating the plasma at higher pressures. In a regular dc glow discharge, this is high pressure operation is usually hampered because at the cathode fall region, a glow-to-arc transitions occurs resulting in destruction of cathode and the plasma device.

However, using the pd restriction, one can tailor the plasma geometry, and expand the operating pressure range of hollow cathode discharge by embedding one hollow cathode structure within another.

THE "WIRE" HOLLOW CATHODE

The "wire" hollow cathode device was designed and constructed to be the plasma source of a UV light source operating at high-pressures [8]. The Figure 1 shows the geometry of the plasma device. The device is consisted of 24 cathode wires made of tungsten, and arranged parallel to each other in a way that they formed a cylindrical structure with a 10 mm diameter cavity. Each wire had 1 mm diameter, and there was a 0.5 mm gap separating them from each. Two insulator disks supported these wires from both ends, and the wires were connected to each other at one end to achieve same applied potential on them.

The disks had 5 mm holes in the middle of them to allow the end-on optical diagnostics. Also, one of the holes contained the 2 mm long, 4 mm inner diameter cylindrical anode. The enclosure of the cathode assembly is a quartz tube allowing the transmission of light emission from the plasma. The plasma device was water cooled from both ends, and there were two end-windows for optical diagnostics.

The device was operated with a dc high-voltage power-supply. The operating gas for the initial experiments was either helium, argon, nitrogen or a mixture of these gases. The pressure range was from 1 mbar to several 10s of mbar, but kept at a constant pressure for each measurement set. The typical current was in the order of 100s of mA. Considering the *pd* restriction, This design allows to generate plasma in the cylindrical volume enclosed by the wires at low pressures (1 to 10 mbar), and in between the wires (in the 0.5 mm gap) at higher pressures.

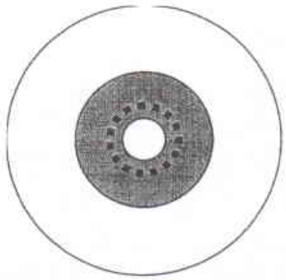

Figure 1. The cross sectional view of the wire hollow cathode device. The outer ring represents the quartz enclosure, the shaded region is the insulator, and the dots represent the wire ends. The middle circle is the opening for the optical diagnostics.

EXPERIMENTAL RESULTS

Operating characteristics of the wire hollow cathode were determined in terms of operating pressure, fill gas, and optimum operating current and voltages. After the initial test, helium gas was used as the fill gas for most of the experiments. The data presented here are obtained with less than 10% nitrogen in helium plasma. It was observed that the plasma operated as a glow discharge at currents approximately less than .3 A, and then started to become hollow cathode discharge. This behavior is show in Figure 2, where the voltage stays at the same value as current increases at values larger than 0.3 A. As seen in Figure 2, this was the same for all the pressure values tested. As a result of these measurements, it was determined that the plasma exhibited the hollow cathode discharge characteristics for any pressure, and currents larger that 0.3 A.. This was also verified by visual observation that diffuse looking plasma inside the quartz enclosure moved completely inside the hollow cylindrical cavity formed by the wires after the current reached values larger than 0.3 A.

Also it was visually observed that the plasma moved from the center of the cavity towards the wires and established in the gaps between the parallel wires at pressures higher that 40 mbar. However, we do not have current-voltage data of this case to present in this paper.

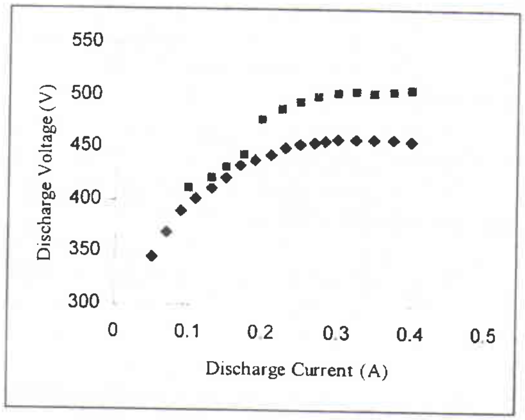

Figure 2. Voltage current characteristics of the wire hollow cathode discharge Diamond shaped data are obtained at 1 mbar pressure, and squares data are at 20 mbar pressure.

Optical diagnostics were conducted using a 0.5m spectrometer, and recorded using a cart recorder. The spectroscopic investigation of the emitted light from the 10% nitrogen in helium plasma in the spectral range between 200 nm and 800 nm showed the first negative system of the molecular nitrogen ion with over 80% of the total fluorescent intensity. There were no other major molecular emission bands or atomic lines in the spectrum. The main excitation mechanism of the first-negative system is due to the charge transfer collision processes from molecular helium ions generated in the helium plasma to the ground sated nitrogen molecule given by the following reaction.

$$He_2^+ + N_2 \rightarrow N_2^+ (B^2\Sigma) + 2He \qquad (1)$$

Then the reaction (1) is followed by de-excitation of the vibrational states of the $(B^2\Sigma;\nu'')$ sate to the vibrational states of the $(X^2;\nu')$ state, resulting in high efficiency light emission in the UV.

Radial mapping of the individual lines emitted from the plasma at lower pressures showed that the excitation took place in the center of the cylindrical cavity. Figure 3 shows a typical plot of the radial distribution of the light intensity at 391.4 nm at 1 mbar pressure operated at 0.35A current. We were not able to record any radial profile of the light emitted from the discharge at higher pressures, because the plasma moved to the sides of the cavity at higher pressures. Thus this region of the cavity was not accessible to our optical diagnostics equipment due to the small diameter of hole on the end-insulator.

In this figure, it is observed that the light emission had an asymmetric shape. This was due to the "hot" spots observed on some of the wires at the time of the measurements. In general, these curves posses symmetric shape indicating the plasma concentrating in the center of the cavity.

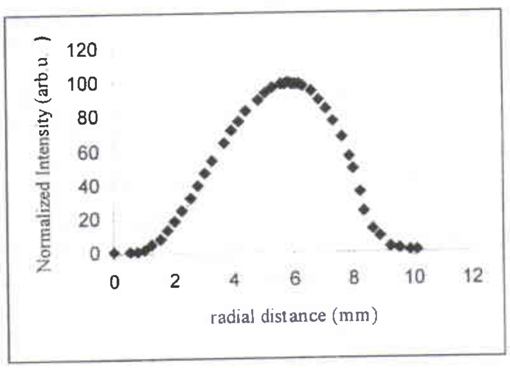

Figure 2. A typical radial intensity distribution of the light emitted from the plasma device. Pressure was 1 mbar, and the current was 0.35 A for this data.

CONCLUSIONS

A wire hollow cathode device was designed, constructed and operated for a wide range of pressures. The device has shown promise to generate high efficiency UV radiation. Hollow cathode discharge operation of the device has been shown, and optical diagnosties of $He+N_2$ plasma performed. These measurements have shown that the charge exchange collisions are effective excitation processes. Future research include operating the device with other gases candidate for UV light emission, and show the effectiveness of hollow cathode discharges for next generation light sources.

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