Linear Arc Discharge (LAD) - Radio Frequency Hollow Cathode Plasma Source for Low Pressure Processing

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ABSTRACT

A new type of linearly scalable the radio frequency (rf) plasma source for plasma processing is introduced. The source is based on the rf generation of a hollow cathode discharge between two parallel plates in a focusing magnetic field. The gas is admitted through the slit between the plates and uniformity of the discharge is controlled by the magnetic field configuration. Experimental results for laboratory prototype of the Linear Arc Discharge (LAD) source with 10 cm long plates, supplied by a 13.56 MHz max. 1.8 kW radio frequency (rf) generator are presented. An rf impedance probe was used to study the character and performance of the discharge varying the rf power, gas flow, gas pressure and geometry. Distribution of the optical emission along the outlet parts of Ti plates was measured to examine uniformity of the discharge and the metal flux. The temperature along the plates was simultaneously monitored by pyrometer. The LAD represents a linear source exhibiting discharge features similar to the Rf Hollow Cathode Plasma Jet (RHCPJ) thereby extending RHCPJ abilities to the large area processing.

INTRODUCTION

An intense gas discharge at reduced pressure generated by the dc voltage in a rectangular hollow cathode was described first in 1916 by Friedrich Paschen [1]. A clear experimental evidence of an effect of hollow geometry in a parallel-plate hollow cathode was reported in 1954 by P.F. Little and A. von Engel [2]. In this report a dramatic increase of the dc current in the discharge circuit (almost 10^3 times) was measured when the plates of the double cathode were gradually brought together and approached a particular distance (several mm) from each other. It means that at the same dc potential between anode and cathode one can obtain about 1-3 orders of magnitude higher discharge current and corresponding plasma density just by providing suitable geometry of the cathode. Hollow cathodes represent therefore very effective sources of the gas discharge plasma for variety of applications in the plasma-assisted processes.

An intense glow produced by dc hollow cathodes has been for quite long time used mainly as a light source for spectral emission analyses (see e.g. [3 - 5]). However, due to extraordinary properties of hollow cathode discharges a lot of effort has been already devoted to the detailed study of their properties and applications, see e.g. review papers [4 - 6], special chapters in handbooks [7, 8], or monograph [9]. Most of published works before 1980 have described hollow cathode discharges generated by the direct current (dc) power. Although several authors reported possibility of using an alternating current instead of dc, as to our knowledge the hollow cathode discharge generated by the radio frequency (rf) power was reported first in 1983 by C.M. Horwitz [10]. Later reports described different arrangements of the rf hollow cathodes, e.g. [11, 12]. In 1985 we patented an original system based on plasma activation of the gas forced through the small nozzle in a capacitively coupled rf electrode operating at reduced gas pressure [13]. This system noted as the Radio-frequency Hollow Cathode Plasma Jet (RPJ or RHCPJ) was studied in different regimes and its versatility in the plasma processing technology was reported, see e.g. review [14]. A great advantage of the small size rf hollow cathodes is their ability to transport active plasma into inside of hollow substrates and pipes. At the same time the hollow cathode can serve as a target for sputtering and/or evaporation of the cathode metal, which can be utilized for the reactive or non-reactive deposition of films inside tubes [15]. Advanced regimes in the RHCPJ system were found at high power, where a dominant role in overall production of electrons is played by the thermionic electron emission from hot walls of the cathode target. The arc regime of the hollow cathode can be used e.g. for the vacuum arc deposition of metal coatings without any working gas [16] or for a high rate metastable-assisted deposition of films [17].

A typical hollow cathode is of a limited size. A new trend in the hollow cathodes is therefore their scaling-up for the large area plasma processing. A simplest possibility is an association of individual cylindrical hollow cathodes into linear arrays, see e.g. [18, 19]. However, a great disadvantage of such arrays is their dependence on stable function of each individual cathode. More suitable geometry for uniform large area processing is a parallel-plate cathode forming a long linear slit. A dc version of such a type of the hollow cathode was described in [20].

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Low power rf slit cathode in a magnetic field parallel with the slit was described in [21]. System of several linear slits was patented in 1994, [22]. However, all systems mentioned above were designed and used for cold cathode processing, e.g. sputtering, dry etching, etc. An advantage of these systems is simplicity and linear scalability, while an obvious disadvantage, particularly in dc arrangements, is problematic ignition.

As to our knowledge, no scalable hot hollow cathode arcs for industrial applications have been reported yet. We have developed recently a novel system with scalable linear slit rf hollow cathode in the focusing magnetic field (see [23, 24]). The system is named the Linear Arc Discharge (LAD) source. In this work we will describe recent results obtained with the laboratory prototype of the LAD source with 100 mm long slit.

PROTOTYPE OF AN EXPERIMENTAL SYSTEM WITH THE LINEAR ARC DISCHARGE (LAD)

The LAD system is schematically described in Fig.1. Two Ti plates 2 mm (and 4 mm) thick and 100 mm long were fixed on a holder mechanisms allowing an adjustable distance of 2 - 5 mm between the plates. The holder was installed in a cathode cartridge mounted in the vacuum reactor pumped by a system of mechanical pumps (Roots blower 800 l/s and the rotary pump 80 m^3/h) with an automatic pumping speed controller. The working gas was admitted into the slit between the plates and the gas pressure in the reactor was held at selected value in the interval between 50 and 750 mTorr. Contrary to the most obvious axial orientation of the magnetic field in the hollow cathode experiments, e.g. [25], the LAD source utilizes magnetic field oriented across the cathode plates and located near the outlet of the slit cathode. The field is produced by the parallel arrays of NdFeB magnets at both sides of the cathode. This arrangement of the magnetic field is extremely important because:

(i) it supports the pendulum motion of electrons as well as an ion bombardment of the cathode walls;

(ii) it focuses the discharge close to the outlet of the slit cathode thereby increasing the power density, and

(iii) it enables to focus linear hot zones created along the cathode plates. The temperature along the hot zones can be very uniform due to both the magnetic field and the heat transfer in the metal plates.

Therefore at high power levels, i.e. at hot cathode regimes, when the thermionic electron emission is dominant, heat transfer in the metal cathode plates automatically (spontaneously) assures a linear uniformity of the discharge produced by the LAD source. The heat conductivity of the cathode plates balances the temperature and consequently the thermionic emission from the linear hot zones. At such conditions the source operates with an enhanced production of metal ions. The high power operation brings about material and construction limitations and our first LAD source described here allows only short time operation at the rf power > 1 kW. The film deposition experiments were therefore carried out at max. 1.2 kW. Duration of the film deposition experiments was 5 min. The maximum power of our rf generator (13.56 MHz) was 1.8 kW.

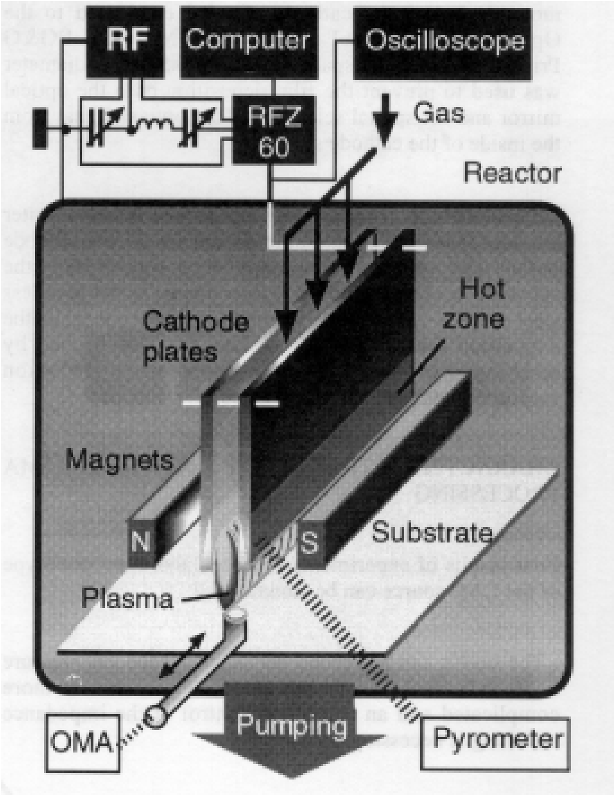

Figure 1. Schematic sketch of the experimental arrangement with the LAD source.

The incident rf power, voltage, current, as well as the impedance data (resistance, reactance, phase angle, reflection coefficient and the angle of the reflection coefficient) were measured by an rf impedance probe (RFZ-60, Advanced Energy). The dc self bias was detected by an oscilloscope (100 MHz, HP 54501A). Optical emission spectra from the discharge were acquired by especially designed optical line with an Al mirror movable below the cathode slit and connected to the Optical Multichannel Analyzer (OMA III, EG&G Princeton). A tubular space selector of 0.5 mm in diameter was used to prevent the film deposition onto the optical mirror and for spatial selection of the optical signal from the inside of the cathode slit.

Deposition experiments were performed using a water cooled table with an alterable distance from the cathode outlet. The separate aluminium block was used as the substrate holder. The holder was equipped by the stainless steel strips both to fix the silicon wafers and to serve as the deposition masks. The film thickness steps formed by masking were used for the thickness distribution measurements both along and across the film area.

CHARACTERIZATION OF THE LAD FOR PLASMA PROCESSING

First results of experiments with the laboratory prototype of the LAD source can be summarized:

- The source can be ignited very easily at the gas pressure > 30 mTorr. At lower gas pressure the start is more complicated and an additional control of the impedance matching is necessary.

- The source is very stable during operation. However, an impedance matching control is desirable during first two minutes of operation due to successive heating up of the cathode plates and approaching the thermal balance.

- The magnetic field can effectively control both the position and the geometry of hot zones at the cathode plates. This is very important feature for industrial utilization of LADs. The outlet parts of the cathode plates consumed for the film deposition during the arc evaporation can be continuously supplied by successive movement of the plates into the magnetic field.

- The ignition of the hollow cathode discharge in the LAD source without magnetic field is very complicated, in most cases impossible at all.

- Impedance of the plasma in the LAD source depends on the experimental parameters. At low rf power the impedance has capacitive character while an inductive component in the total reactance becomes more pronounced at rf power exceeding 300 W during LAD operation

- As we have already reported [24], at low rf power ≤ 1 kW the present prototype of the LAD source cannot operate in a fully developed arc regime. The temperature along the hot zones at the Ti plates is less than 1150 °C. For the stable arc in Ti hollow cathode it is necessary to reach values exceeding 1350 °C [16, 17].

- The source produces ion rich plasma. The most intense lines in the optical emission spectra of the LAD at rf power ≥ 1 kW are often Ti^+ ions, depending on the discharge parameters.

A simple densitometric scanning of the light from the photography of the LAD discharge is shown in Fig.2. The geometry of the area of the intense light corresponds very well to the geometry of the area deposited by the Ti film.

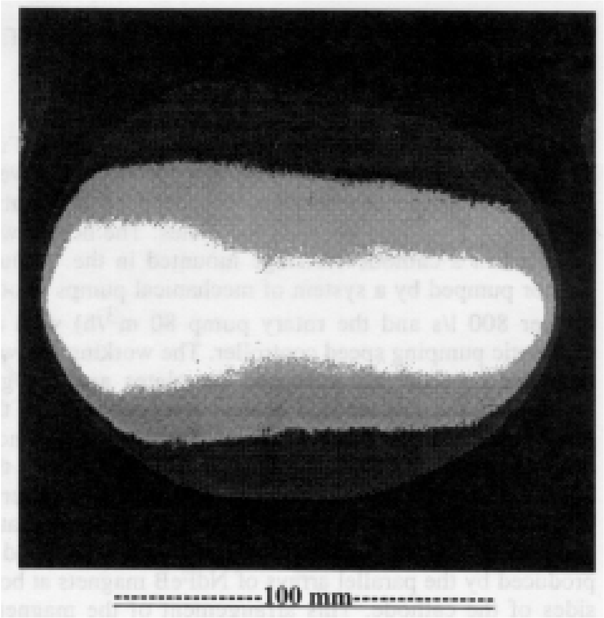

Figure 2 Scanned photography of the LAD discharge below 100 mm long 3 mm wide slit hollow cathode. Rf power 1 kW, 1000 sccm Ar, 250 mTorr, induction vector **B**(+).

A linear uniformity of the optical emission from the discharge along the LAD slit was examined at different experimental conditions by the movable optical system. Optical emissions from Ti (λ = 3653.5 Å), Ti^+ (λ = 3685.2 Å), Ar (λ = 4158.6 Å) and Ar^+ (λ = 4103.9 Å) lines were used. The distribution of the optical emission was compared with the corresponding distribution of thickness of the deposited Ti film. It was found that side parts of the cathode plates act as additional hollow cathodes thereby increasing both the temperature on the side edges of plates and the optical emission intensity with respect to the central part of the slit. As a consequence the film growth rate at side parts of the LAD is higher than that in the central part, as we have reported elsewhere [24]. It was also found that the distribution of intensity of the optical emission lines of Ti and Ti^+ can be well correlated with the Ti film growth rate and consequently with the resulting distribution of the Ti film thickness at the substrate. The best fit can be obtained using the sum of Ti + Ti^+ intensities.

The problem of the side nonuniformities of the discharge is now under intense study. We have already found that even in the simple construction of the present LAD prototype the side non uniformity of the discharge or the discharge symmetry can be affected by different experimental parameters, e.g. by the gas flow rate through the cathode, by the rf power, and the geometry of the focusing magnetic field. This finding is very important for the uniformity control in the LAD sources. For example, at rf power of 900 W and Ar pressure 0.25 Torr the experiment shows that the symmetry of the discharge and the corresponding film growth rate are better at low Ar flows (< 10 sccm) as compared with medium flow rates (about 100 sccm). The uniformity of the discharge is slightly better as well. An example of profiles of the optical emission for the sum of Ti and Ti^+ intensities along the slit at three different Ar flow rates is shown in Fig.3.

The distribution of the discharge is affected mainly by the magnetic field. The magnetic field affects movement of Ti^+ ions and Ar^+ ions which have velocity component perpendicular to the magnetic induction vector **B**.

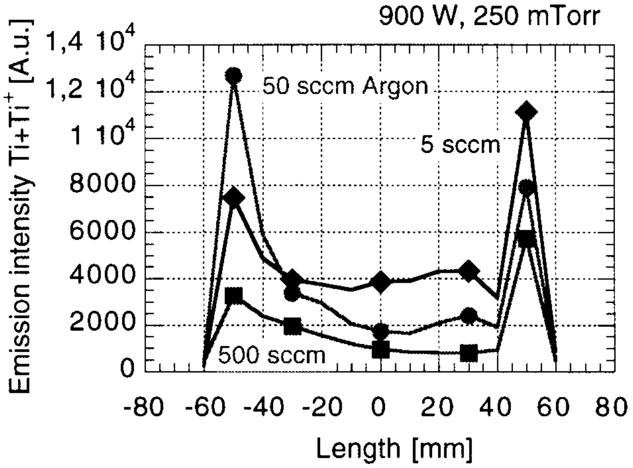

Figure 3. Distribution of the optical emission intensity of Ti + Ti^+ along 100 mm long slit of the LAD at different Ar flow rates.

Assuming the gas flow velocity ≤ 100 m/s (depending on the gas flow rate) the corresponding cyclotron radius of ions in our experimental conditions can reach several millimetres. The resulting shift of the discharge might be of the order of 10 mm which is only 10 times less than the length of the slit in our laboratory LAD. It can therefore affect the resulting distribution of the film thickness. There is however an electric field between the cathode plates and the surrounding rf plasma which also pushes the ions to move perpendicularly to the vector **B**. The detailed mechanisms of the resulting production of Ti species and their distribution along the cathode outlet is therefore complex. We are not able to explain the gas flow effect on the film thickness distribution yet.

Fig.4 shows how the Ti film distribution along the substrate is affected by different orientation of the induction vector **B**. It means that optimization of the linear uniformity of the discharge can be accomplished by proper configuration e.g. segmenting of the magnetic field. This optimization will be easier for long LAD sources by suitable segments of small size permanent magnets.

The Ti film growth rate measured 30 mm below the LAD outlet depends on the rf power. At rf power of 1 kW the maximum growth rate up to 200 nm/min was detected. It is to be noted however, that at short time overloading of the source up to 1.8 kW the extremely high maximum rate of 10 µm/min has been found at the substrate distance of 5 mm from the LAD outlet. This very high rate is reproducible, but due to material limitations in our laboratory prototype certain improvements in the construction are necessary for high power LAD operation.

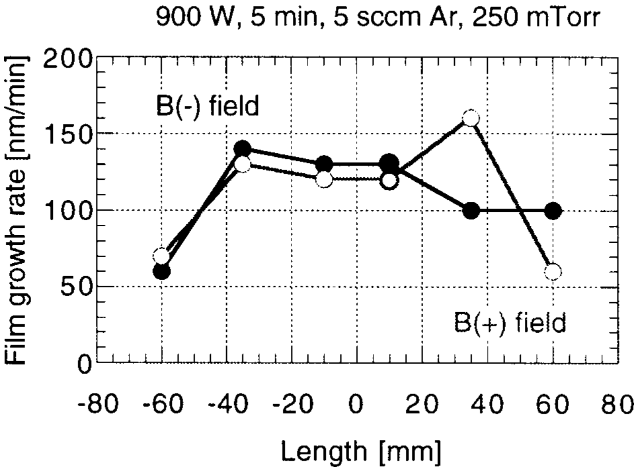

Figure 4. Distribution of the Ti film growth rate along the substrate 30 mm below 100 mm long slit of the LAD at opposite oriented magnetic fields.

CONCLUSIONS

The Linear Arc Discharge (LAD) source based on the radio frequency generated hollow cathode with the parallel-plate geometry in the focusing magnetic field at the outlet of the cathode has been introduced. The magnetic field is of an utmost importance to confine the discharge in the cathode active area which allows a high power density generation of the hot cathode zones where high density hollow cathode discharge is produced. The source is designed basically for the high power hot target operations in arc regimes similar to those in which very high rates of the reactive deposition of TiN films have been observed in small size cylindrical RHCPJ systems [14]. Regardless the limited rf power allowed in the laboratory prototype (≤ 1 kW) first series of experiments confirm that the LAD source exhibits similar behaviour as the RHCPJ. We have already observed for example that in an analogy with the RHCPJ [17] the LAD can also utilize the metastable-assisted regimes for high-rate deposition of TiN films. Reactive depositions of films in LAD are now under detailed study.

The LAD sources are very promising for the large scale plasma processing technology. The construction of the LAD source is very simple in comparison with the well known magnetron sputtering sources. The design allows installation of the source on similar flanges as the magnetrons. Moreover the LAD construction allows simple replacement of the consumed target material in the discharge zone. We believe therefore that LAD sources can be used very soon in an industrial level for generation of an arc plasma for the plasma processing together with or even instead of magnetrons.

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