Evaluation of the Plasma Distribution of a Quasi-Linear Constricted Plasma Source

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Abstract— The quasi-linear constricted plasma source is a downstream plasma source with ten linearly aligned discharge cells. Each cell operates on the basis of a constricted glow discharge. The plasma output can easily be monitored by the plasma-emitted light. The information is not only intuitive but can also be used to operate on-line feedback control of the plasma source which is important for large-area plasma processing of materials.

Index Terms— Constricted plasma source, gas plasma flow, plasma diagnostics, plasma processing of materials.
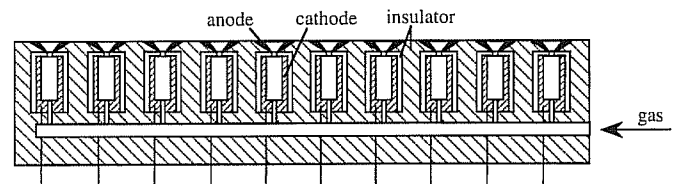

Fig. 1. Schematic of the ten-cell, quasi-linear constricted plasma source. The working gas is fed from the right into a common gas reservoir which is connected to each of the ten discharge cells. Electric power (dc) is provided to each cathode while the constricted electrodes (top) usually work as anode (common).

SURFACE processing of materials is often assisted by suitable sources of ions and activated neutral species, such as downstream plasma sources [1]. This paper deals with a relatively unknown kind of downstream plasma source, the constricted plasma source (CPS), also known as hollow–anode source [2]. Early versions of this source have been introduced by Miljevic and applied as either spectroscopic light sources or, in combination with particle extraction optics, as sources of energetic ions and electrons [5]. The plasma source (without particle extraction system) is characterized by low ion and neutral kinetic energy and is thus well-suited to the deposition of thin films such as GaN [7].

The CPS is based on a special form of glow discharge. Enhanced ionization is obtained by introducing a small aperture or constriction into the discharge path. The constriction is conventionally placed in front of the anode, reducing its active area and forcing the formation of a double layer which acts as a virtual anode [6], [8]. The real anode (constricting electrode) serves as a nozzle, producing a supersonic stream of plasma which contains not only ions and electrons but also activated neutrals such as dissociated molecules (radials) as well as excited atoms and molecules. The CPS can operate with virtually any gas, including reactive gases such as nitrogen and oxygen, and even water vapor has been successfully used.

The deposition of compound films on an industrial scale requires plasma sources capable of delivering copious amounts of plasma and activated neutral species to large-area substrates. In one possible configuration, the plasma is delivered by a linear source, and the substrate is moved with appropriate speed perpendicular to the linear extension. In this way,

large areas can be continuously coated or plasma-treated. Applications include window glass and plastic web coatings.

Recently, a quasi-linear version of the CPS has been developed in our laboratory. The source consists of ten aligned CPS discharge cells which are mounted in a common Teflon® body (Fig. 1). Each cell consists of a hollow cathode nested in a ceramic insulator which in turn is nested in the common source body. Gas is supplied to each cell from a common gas reservoir; a typical gas flow is 10 sccm per cell. The discharge current is typically 50 mA per cell, at an anode-cathode voltage drop of about 400 V. Each cell is equipped with an individual electrical connection to its cathode while the constricting electrodes (nozzles, usually the anodes) of all cells are electrically connected. The constrictions (nozzles) have an inner diameter of 0.75 mm at the narrowest location. They are held by a common plate which is water-cooled (not shown in Fig. 1). The current and power to each cell can be regulated by individual resistors or by using the current-regulating mode of modern electronically regulated power supplies. The cell-to-cell distance of the source is 2.54 cm (1 in), and the overall width of the downstreaming plasma is therefore more than 25 cm.

In on-line processes, monitoring the plasma by Langmuir probes is not advisable because it would disturb and possibly contaminate the plasma. Optical measurements are obviously a good choice, and we report here about plasma monitoring by imaging. The most straightforward method is to position a camera in such a way as to view the downstream plasma; this can also be accomplished by a suitable set of mirrors. Fig. 2 shows the quasi-linear CPS in operation with oxygen. The pressure in the processing chamber was 2 mtorr ($\approx$ 0.2 Pa). The photograph was taken with a Kodak®–Nikon® digital camera using a 35–70 mm zoom lens with an additional macro-lens. The digital card gives a 6 Mb-compressed 2000 × 3000-pixel TIFF file, with 36-bit color per pixel. The picture can immediately be downloaded into a computer and used for evaluation of the plasma. Data such as intensity, color (spectrum), and homogeneity can be extracted.
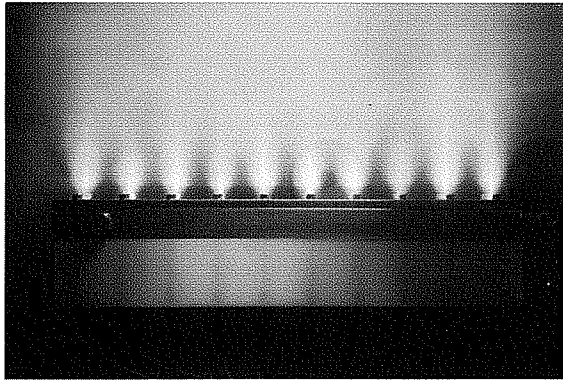
Fig. 2. Quasi-linear CPS in operation with a low flow rate of oxygen of 10 sccm per discharge cell; plasma flows from source (bottom) to top. The plasma beamlets merge for distances greater than the nozzle distances. Nozzle-to-nozzle distance is 2.54 cm.

The use of the advanced digital camera technique is convenient but may be too slow for on-line feedback control. For instance, the uncompressed file of one picture is 18 Mb which requires many seconds of loading and processing, even on today's fast desktop computers. Therefore, more common and affordable CCD cameras with only 1024×512 or even 512×512 pixel and 8-bit resolution can serve efficiently for display and control purposes. This is particularly true when using contrast enhancement and false-color-coding: features available on standard image processing software.

Fig. 3(top) shows a low-resolution image of the quasi-linear CPS operating at low oxygen gas flow of only 4 sccm per channel (chamber pressure 0.5 mtorr or 50 mPa). In this case, the electrode at the constriction was electrically isolated and did not serve as the anode. The source was therefore not in the often-used hollow-anode mode. Most of the voltage drop occurred between the source (constricting electrodes) and the grounded vacuum chamber (anode). The dark space downstream of each nozzle corresponds to the well-known cathode dark space of a glow discharge [9]. One can easily see that the plasma density is strongly modulated for small distances (e.g., 2 cm) from individual nozzles. The bright filament in the dark space adjacent to each nozzle is attributed to excitation caused by energetic electrons generated in the double layer at the constriction. Since homogeneity of the plasma at the substrate is critical for the deposition or treatment process, false-color imaging can reveal important information. Fig. 3(bottom) shows the same picture but color coded. While the plasma beamlets appear to form homogeneous plasma on the nonprocessed picture for distances larger than 10 cm, color coding uncovers modulation even at large distances when operating at low pressure. Color-coded images show that plasma density modulations decrease at higher gas flows and pressure. Fig. 3 shows the worst case in terms of plasma homogeneity but the most interesting to plasma imaging. Independent Langmuir probe measurements confirm these findings and provide approximate calibration: the highest plasma density 10 cm downstream from the nozzle is about
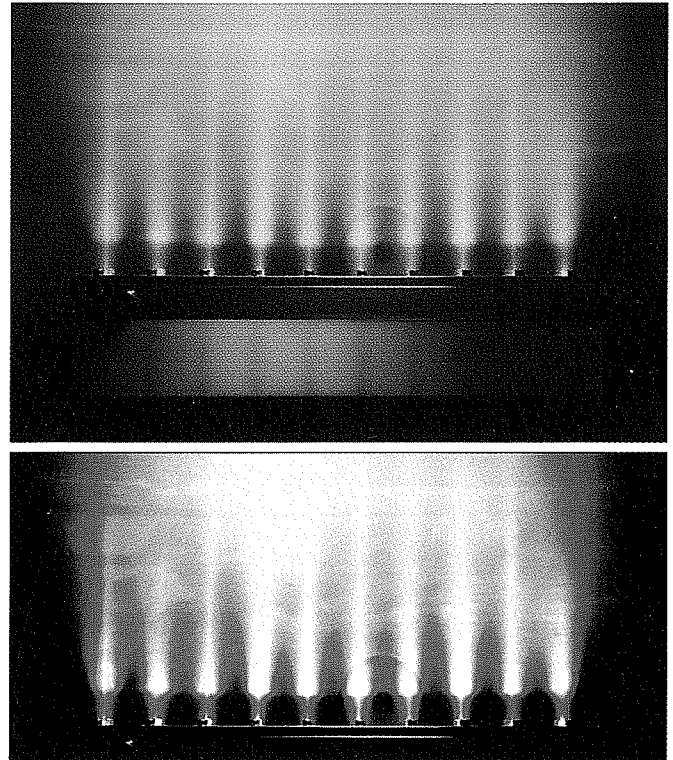

Fig. 3. (top) Quasi-linear CPS operating at low oxygen gas flow of 4 sccm per discharge cell. (bottom) Part of the same picture but false-color coded, emphasizing the plasma inhomogeneity at large distances from the nozzles.

10^8 cm^{-3}, with modulations up to a factor of two. The information derived from color-coded images can be used to generate feedback signals to the source power supplies and gas flow regulators, thus stabilizing the output and improving source performance.

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