Intelligent Control of Low Pressure Plasma Processing

J. Al-Kuzee, T. Matsuura, A. Goodyear, L. Nolle, A. A. Hopgood, P. D. Picton, and N. St. J. Braithwaite

Abstract— **Several parameters characterize systems for materials processing that use radio frequency electrical discharges in gases at low pressure. These include directly measurable quantities such as a DC bias voltage, an ion current, an energy flux, masses of charged species, and spectrally resolved optical emission. None of these is directly controllable but all are dependent on several variables that can be controlled such as radio-frequency (RF) power, chamber pressure, and gas flow rates. There is a rich parameter space that must be painstakingly searched for optimum conditions for any particular process. In place of the relatively slow manual procedure, an artificial intelligence (AI) approach has been used to map out contours for all of the above characteristic parameters in the control space. Automatic characterization of plasma systems in this way could significantly reduce the time to re-configure them and to transfer processes between different systems.**

I. INTRODUCTION

PLASMA processing is an important technology in materials processing, particularly in the semiconductor industry. The implementation of extensive control in plasma processing has the potential to bring benefits in the form of improved quality and production rate. Control of such systems needs robust diagnostics in conjunction with versatile supervision. A flexible artificial intelligence (AI) approach to computer control of plasma processing offers a way to control and optimize the complex plasma environment without some of the restrictions associated with traditional control [1], [2]. In this way automatic control of a plasma process in terms of the absolute ion energy flux onto a substrate is straightforward [3].

Plasmas are gases containing free charges, ions and electrons, though like lumps of solid conductor they are overall electrically neutral. Plasma processing uses electrical energy, mediated by free electrons, to deconstruct the molecules of a gas into atoms and molecular fragments, many of which are also ionized. The important interactions of these species with surfaces include bombardment by energetic ions (and photons) and reaction with chemical radicals.

In this paper, a parameter search in terms of power, pressure, and the composition of mixture of two gases is introduced. This approach is fully described in section III.

II. SYSTEM

A 13.56 MHz capacitively-coupled RF plasma system is used (Fig. 1). Typical discharges are obtained in the power range of (30–300 W), gas pressures of (1–40 Pa, 10–300 mTorr), nitrogen flow rates of (3 – 100 sccm), and argon flow rates of (10 – 70 sccm). Measurements of pressure, nominal power, gas flow rates, DC bias, ion flux, chemical species ratio, and optical emission spectrum intensity ratio (a characteristic voltage arising from nonlinear plasma behavior) are passed to the AI controller. Settings for power, pressure, and mass flow rates for two gases are returned from the controller to the system.

The most easily integrated diagnostic tools produce a DC analogue signal proportional to the measurement. The signal generally has a high response speed and can quickly be read by the process controller. In this system, it is fed to the A/D converter input of a data acquisition system and transferred to a controlling processor. AI can be applied to any diagnostic tool having this form of output simply by setting the appropriate values for offset and span.

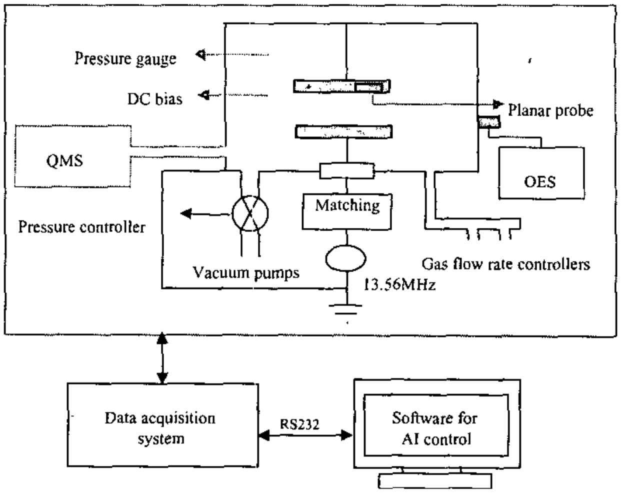

Fig. 1. Schematic of computer controlled RF plasma system with associated diagnostics.

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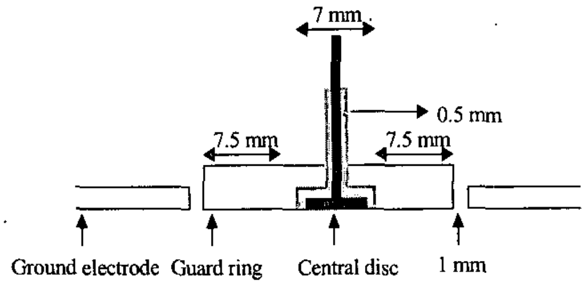

Fig. 2. Schematic of guarded planar probe.

An electrostatic planar probe was used to determine the total positive ion flux to the surface of the ground electrode. The probe is a large area single sided disc with a guard ring around it.

The guard ring is maintained at the same potential as that of the central disc to remove edge effects. The probe is embedded into the ground electrode. The probe is biased at –9 volts DC into the ion saturation regime where the electron flux is negligible so its signal is a direct measure of ion current, reflecting the density of the plasma. The probe construction is shown in Fig. 2.

Optical emission spectroscopy (OES) and quadrupole mass spectrometry (QMS) systems have been integrated into an AI plasma control system. OES was used to monitor light emission from the plasma. It provides rich, but highly convoluted information about properties such as species densities, electron-atom, atom-atom, ion-atom collisional effects, and the energy distribution of species. The use of OES in the diagnosis of low density and low temperature plasmas is widespread [4] and has yielded a great deal of information about the properties of materials within plasmas. Its application to plasma processing applications such as semiconductor etching has been used along with other diagnostics to direct researchers and engineers in the pursuit of ever-smaller features in semiconductor devices. QMS was used to provide information on atom, molecule and ion masses and their concentrations in the system.

In the OES, the wavelengths of particular species of interest in the plasma are pre-selected. The OES tool scans a range of wavelengths between (180-850 nm) every 80 ms. The intensities of desired wavelengths were selected using a digital delay generator and were then integrated by boxcar integrators into analogue DC voltages.

In the case of the QMS, the analogue outputs are scanned for the mass number and the corresponding intensity in units of the partial pressure are used. For the QMS two mass species were selected and for the OES two lines were taken. Use of the ratio of two signal intensities compensates for any efficiency factor in the converting circuit and it also yields more information about the plasma.

III. SOFTWARE

Concern for controlling important industrial processes based on plasma technology through the use of a diagnostic measurement system has increased during the last few years. Previous work reported by [5], [6] and many others involved the use of three and seven harmonics for a real-time waveform synthesis as part of an electrostatic diagnostic probe for measuring plasma parameters. In matching a waveform with seven amplitude variables and seven phase variables an AI approach has proved particularly effective.

N. St J. Braithwaite et al. [7] involved the use of a search parameter in terms of power- pressure parameter space. They introduced a parameter search contour for the positive ion flux in hydrogen and argon plasma for fixed mass flow rate of 25 sccm.

In this current work, a search parameter in terms of power, pressure, and the composition of a mixture of N_2 and Ar is introduced. The search parameter is used to find the ion flux, DC bias, ion energy flux, the ratio of two chemical species using the QMS, and the intensity ratio of two emission lines using the OES. The search parameter is also used to examine the existence of the hysteresis loops in the plasma.

Parameter searching has been implemented using C++. A point in the parameter space is initially chosen at random. The gradient descent method is used to find a point on the contour to be traced by examining the local gradients of the search space in each direction. A contour-following method for mapping variables in space is then introduced. A prediction is made as to the location of another point near the contour. Initially it is assumed that the line followed by the gradient descent is the steepest slope and is hence perpendicular to the contour at the point of intersection. The gradient descent algorithm is then used to locate the contour again starting from an estimated point. Once two or more points have been located on the contour it becomes possible to employ other methods of estimating the next point on the contour such as linear and quadratic interpolations. The flow chart of the basic search parameter algorithm is shown in Fig. 3.

IV. RESULTS AND DISCUSSIONS

The full current-voltage characteristic of the planar probe is fairly flat when the potential is sufficiently negative to reject all electrons from the plasma (< -5 V). The measured current can then be taken as a direct measure of the flux of positive ions to a surface flux and is easily built into a contour-tracking algorithm.

A gas discharge presents a nonlinear load to an RF generator. As a consequence, in response to the RF supplied a DC bias voltage develops across the plasma reflecting the amplitude of the RF and the electrical geometry of the discharge. In fact this DC potential turns out to be a close to that through which positive charge is accelerated as it approaches a surface. The measured potential can then be taken as an indirect measure of the energy of positive ions bombardment and is easily built into the algorithm for contour following.

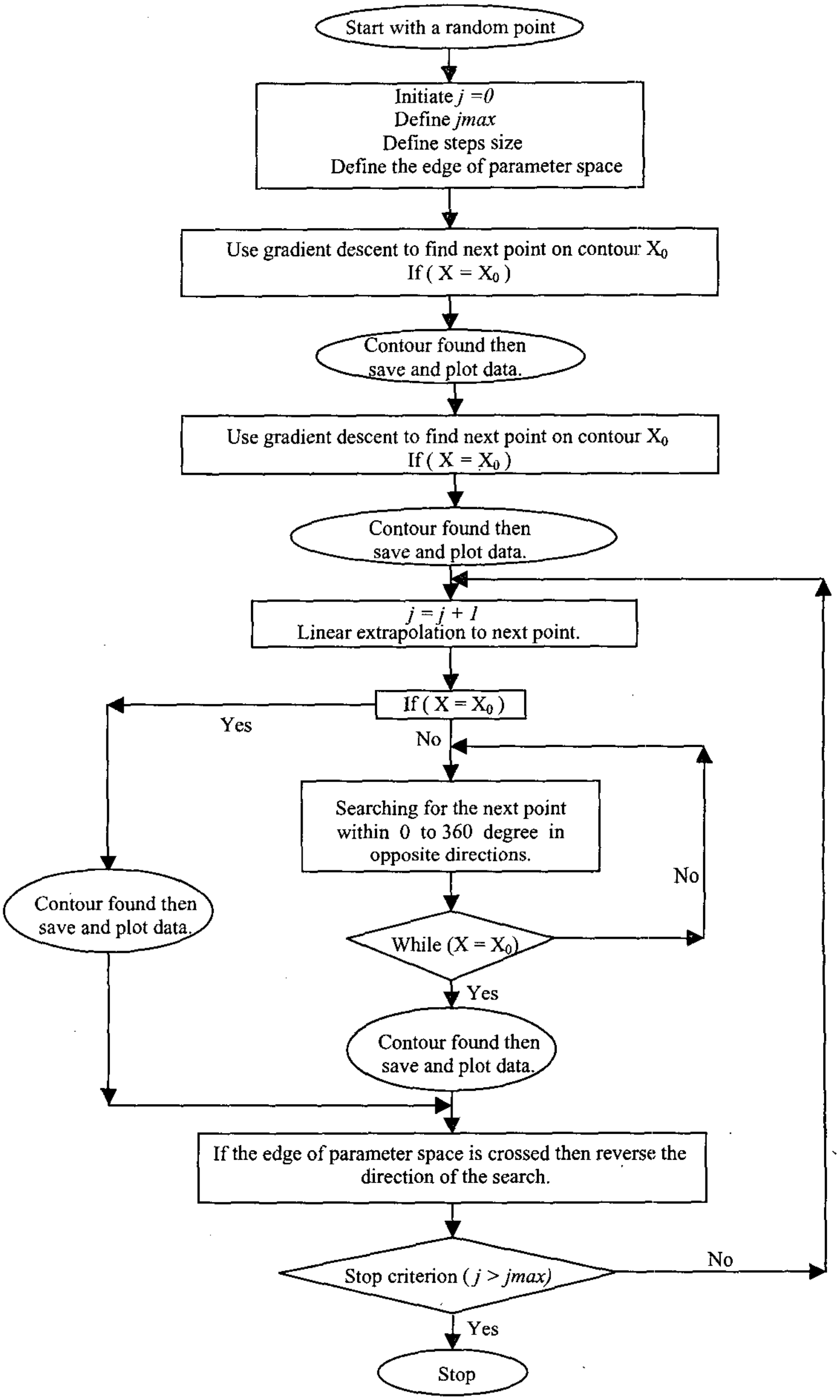

Fig. 3. Flow-chart of the search parameter algorithm.

The product of ion energy and DC bias gives a measure of the energy flux in the ion bombardment. This quality has special importance in materials processing with plasma.

The relative abundance of species can be inferred directly from ratios extracted from a mass spectrum. Optical emission spectra are considerably 'richer' as they involve the sub distribution of the populations according to various states of internal energy (excitation). N_2 (28 a.u.) and Ar (40 a.u.) were measured by the QMS whereas the line intensity ratios of emission at a characteristic nitrogen wavelength 385.7 nm and one from the argon spectrum at 750.4 nm were measured by the OES.

Results of contour following on DC bias, total ion flux, ion energy flux, mass ratios, and line intensity ratios in argon and nitrogen plasmas have been obtained and are shown in figures (4-9). These contours were followed between the limits of the search space in both directions. Parameter space was crossed in both directions to map out any hysteresis loops in the contours. Since measurements and settings of pressure, nominal power, the mass flow rates of nitrogen and argon are passed and returned to the AI controller, care was taken to allow a reasonable degree of tolerance for the setting of power, pressure and the mass flow rates for the nitrogen and argon.

The hysteresis loops on the contours are the results of tolerances in the values of controller outputs, rather than any physical process within the plasma. Fig. 4. shows the hysteresis loop disappearing as the tolerance is tightened.

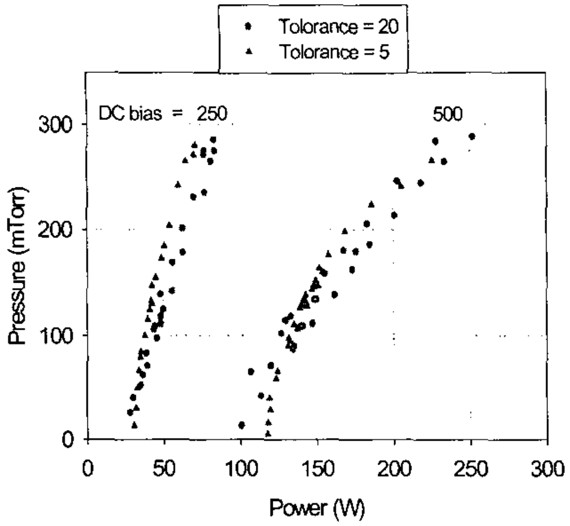

Fig. 4. Contours for DC bias (V). Mass flow rate is 20 sccm of argon.

The selection of an appropriate step width is crucial to the performance of the search space algorithm. If the step width is too small the algorithm takes a long time to finish the search. If the step width is too large then the algorithm takes a shorter time to finish the search but does not necessarily find the required number of points. Care was taken to choose a reasonable step width for the algorithm to find the required number of points. The time taken to determine these contours largely depends on the time taken to change the plasma conditions and measure the parameters. The search contour was designed to find 25 points between the limits of parameter space. The time taken to find 25 points on any contour was between 10 and 20 minutes. The technique reveals strong dependencies of

- a- The ion flux on power.
- b- The DC bias on pressure.
- c- The ion energy flux on power and pressure.
- d- Mass ratios on the flow rates of the two gases and slightly on the power.
- e- The OES intensity ratio on power, pressure and the flow rates of the two gases.

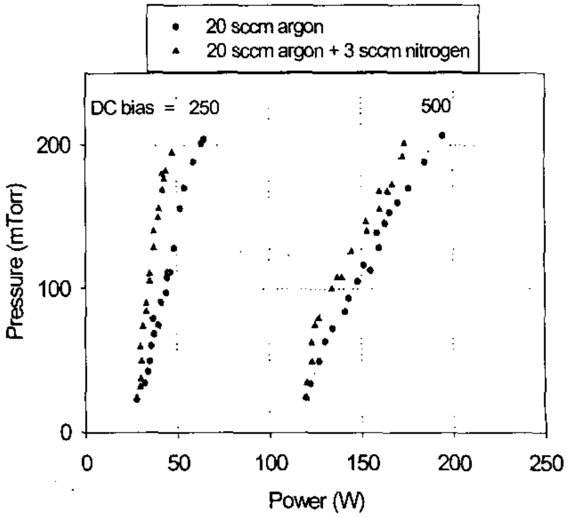

Fig. 5. Contours for DC bias (V).

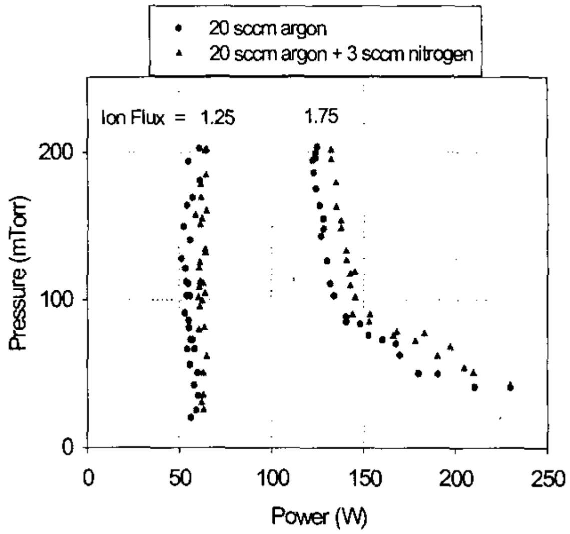

Fig. 6. Contours for ion flux ($A.m^{-2}$).

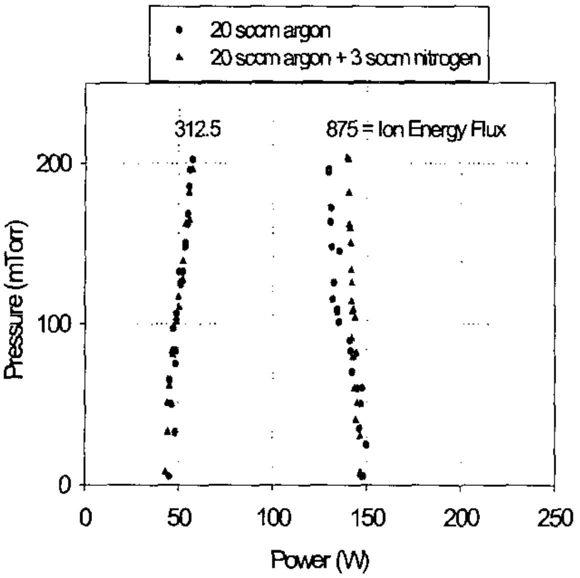

Fig. 7. Contours for ion energy flux (V.A.m^{-2}).

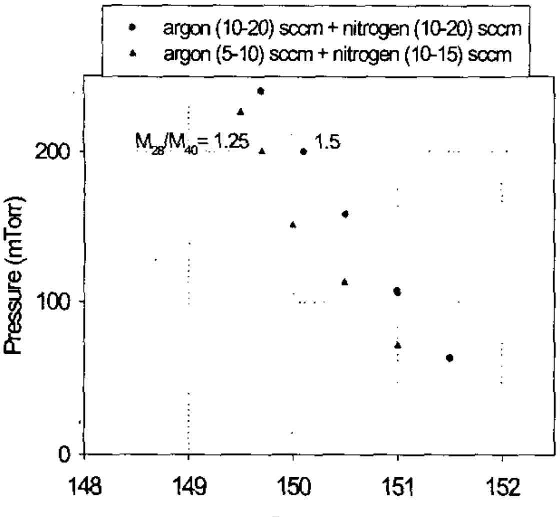

Fig. 8. Contours for gas ratio.

It should be emphasized that the mapping of these parameters by AI control is considerably easier than the manual method. It also provides a graphic characterization of the system. It is easy to see the scope for automatic bench marking of new systems or the recalibration of systems following maintenance and clearing cycles.

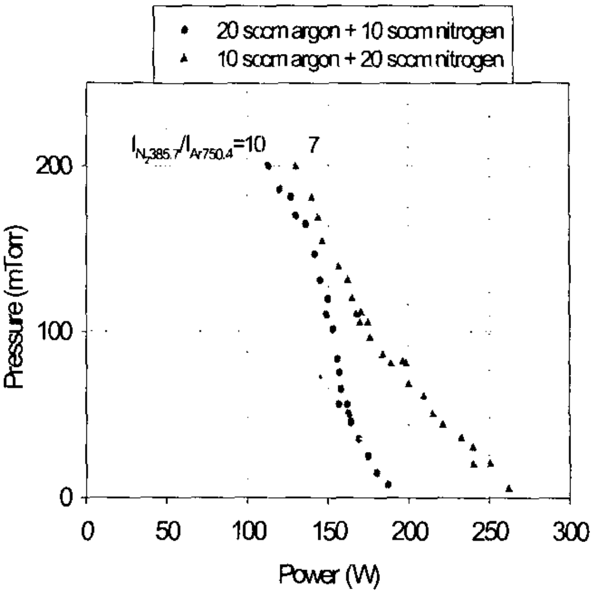

Fig. 9. Contours for line intensity ratio.

V. CONCLUSIONS

Results of contour following on DC bias, total ion flux, ion energy flux, mass ratios, and line intensity ratios have been obtained for argon and nitrogen plasmas. Contours were followed between the limits of a search space in both directions. The contour following algorithm reverses the direction of the search process when the edge of the specified parameter space is crossed. The time spent measuring a contour is largely dependent on the time taken to change plasma conditions and measure the variables, rather than the contour algorithm internal calculations.

Tolerance and step size are important for the performance of the parameter space algorithm. The parameter space search has always found better solutions than human operators, and has also achieved these in significantly less time.

Various diagnostic measurements, including optical emission spectroscopy and a quadrupole mass spectrometry have been integrated into an AI control system. Without necessarily understanding the detailed physical and chemical processes involved, robust control of key processing parameters has been demonstrated. The system can also form a tool for verifying the relationships between variables in a plasma predicted by theoretical or numerical models. In principle, the method can be applied equally to the control of any plasma processing system whose behavior is a function of many variables, provided that the state of any such system is dependent solely on the instantaneous values of these variables, and not their prior history.

ACKNOWLEDGMENT

This work is funded by the Engineering and Physical Sciences Research Council (EPSRC) under grant reference GR/M71039/01. The authors would like to thank Dr. Jan Kowal for valuable discussions and helping in the preparation of the paper.

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