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Reactive gas control of non-stable plasma conditions

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Abstract

Most industrial plasma processes are dependant upon the control of plasma properties for repeatable and reliable production. The speed of production and range of properties achieved depend on the degree of control. Process control involves all the aspects of the vacuum equipment, substrate preparation, plasma source condition, power supplies, process drift, valves (inputs/outputs), signal and data processing and the user's understanding and ability.

In many cases, some of the processes which involve the manufacturing of interesting coating structures, require a precise control of the process in a reactive environment [S.J. Nadel, P. Greene, "High rate sputtering technology for throughput and quality", International Glass Review, Issue 3, 2001, p. 45. [5]]. Commonly in these circumstances the plasma is not stable if all the inputs and outputs of the system were to remain constant. The ideal situation is to move a process from set-point A to B in zero time and maintain the monitored signal with a fluctuation equal to zero. In a "real" process that's not possible but improvements in the time response and energy delivery could be achieved with an appropriate algorithm structure.

In this paper an advanced multichannel reactive plasma gas control system is presented. The new controller offers both high-speed gas control combined with a very flexible control structure. The controller uses plasma emission monitoring, target voltage or any process sensor monitoring as the input into a high-speed control algorithm for gas input. The control algorithm and parameters can be tuned to different process requirements in order to optimize response times.

Keywords: Sputtering; Reactive; Feedback control; PEM

1. Introduction

Feedback control applied to reactive sputtering was firstly introduced by Chapin and Condon [1] in 1978 where both optical emission intensity of a particular element or target voltage were monitored in order to control the reactive gas to be introduced. A basic model of a reactive magnetron sputtering process was described by Berg and co-workers [2–4] back in the late 1980s. The basic mass balance of the reactive gas gives the first principles of how to control this process (see Fig. 1). In this process balance it is assumed that the reactive gas input "ends" up in three zones: part of it would be on the target and plasma area (not necessarily ending up there), a second part will end up as a coating on the substrates and chamber walls, and a third part will be the unreacted gas which will be pumped away. In order to monitor and control this system, one or more of these characteristics will need to be measured. For example monitoring the target voltage or frequency (if pulsed or AC powered), or plasma emission (colour or intensity at a particular wavelength — such as of the target material atoms or reactive gas) yields data relating to the gas near the target. The coating on substrate can be monitored by measuring

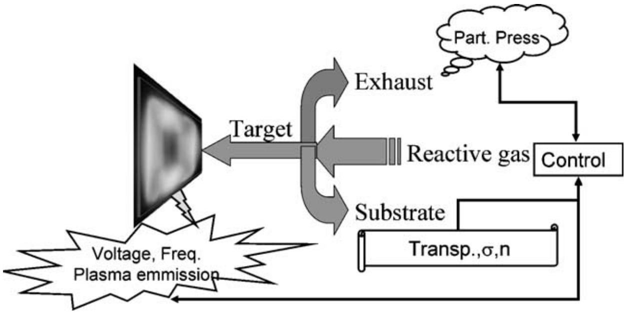

Fig. 1. Basic reactive sputtering model and control options.

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transparency, refractive index or conductivity. The "exhaust" can be measured via the reactive gas partial pressure. If this data is fed-back, and then either the reactive gas input or target power is acted upon (for example), closed loop control can be generated.

The intention of this paper is to present a new approach to reactive sputtering control via what is called Pseudo-Derivative Feedback (PDF) control, which due to its inherent properties is able to respond to the demands of the system in critical damping conditions with the fastest possible speed.

2. Modeling the control system

2.1. The basic automatic control system

A basic automatic control system could be described by the way of block diagrams as per Fig. 2.

It is of interest to start to look at the simple harmonic motion as a starting point for the formulation of control. In most of the process which require control there is a need to provide energy or change to the system. Generally those changes away from equilibrium conditions would introduce perturbations, which, when trying to be compensated could be model as a "spring" and a "shock absorber". The reason is that in reactive sputtering gas controlled it is possible to recognize forces that would make the system to oscillate (spring action) and forces which would produce a damping effect on the harmonic motion (stiffness).

When an external force, F, is applied to this system then the overall equation will become (Fig. 3):

$$MD^2x + sDx + kx = F. \tag{1}$$

This model introduces two concepts:

1. Critical damping, for which in a set of conditions it will be possible to arrive from position A to position B in the minimum time.
2. Resonance, for which the delivery of energy is optimum.

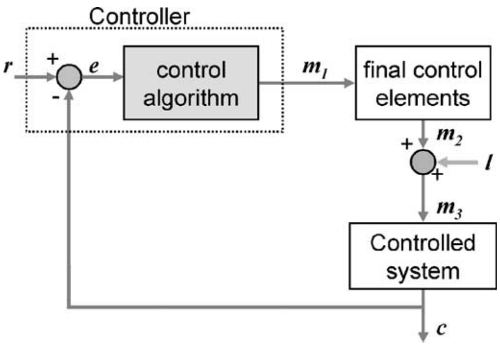


Fig. 2. The basic automatic control system described using block diagrams.

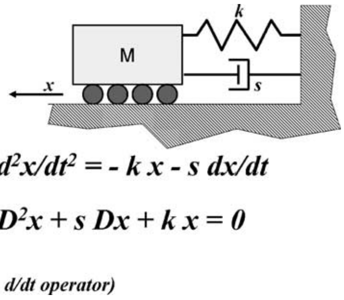


Fig. 3. The basic damped harmonic system.

By applying the nomenclature for operational control we could replace the previous parameters by the following ones:

a) mass is replaced by Inertia, "*I*"
b) space variable is replaced by the controlled variable "*c*"
c) the oscillative tendency around the setpoint is described by "*k*"
d) the damping rate effects are described by "*a*".
e) the force which moves the system is described by the manipulated variable "*m*".

In this way the general differential equation applied to this control system would be (Fig. 4):

$$ID^2c + aDc + kc = m \tag{2}$$

which in operational form will be:

$$\left(ID^2 + aD + k\right)C = M \tag{3}$$

depending on the order of the controller we can define from Fig. 5 three types of systems.

a) zero-th order controlled system
b) first order controlled system
c) second order controlled system.

3. Pseudo-Derivative Feedback (PDF)

3.1. The standard controller

For a First order controlled system the standard feedback loop control block diagram could be describe by Fig. 6. First order controlled systems tend to be more difficult to control

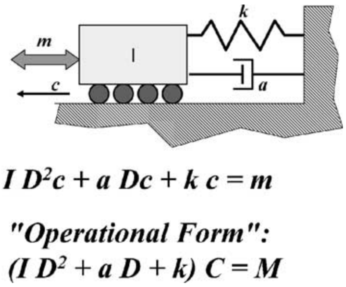


Fig. 4. Operational form for a forced oscillator (2nd order controller).

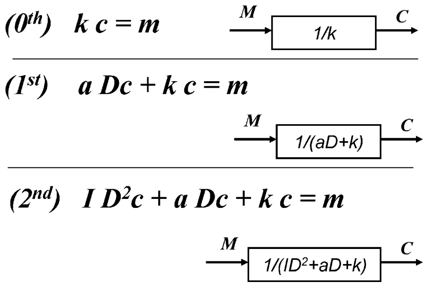


Fig. 5. Different orders of controlled system and operational relationship between the manipulated operation M and the response of the controlled variable C.

than a Second order one. In the traditional way of the controller at least two of the parameters of the algorithm will be involved in the same loop. This would make generally optimisation more difficult than having parameters in separate loop levels.

3.2. The PDF algorithm

More than 30 years ago Richard Phelan [6,7] proposed to divide the feedback from a single loop to a series of control loops. For each of these loops a single algorithm parameter would need to be adjusted. Looking at Fig. 6 the transformation which is fed back to the controller could be divided into two parts, the part that contains the derivative ($K_d D$) doesn't need to be integrated (K_i/D) as that will return to the original. Therefore K_d could be fed in a different route, bypassing the integration as indicated in Fig. 7. This would be a "pseudoderivative" route, therefore the name Pseudo-Derivative Feedback (PDF) control.

By having these two loops separated, a separation of the algorithm parameters is obtained and easier optimisation would now be possible. The overall result is that the final control is able to achieve good levels of control with one less parameter than traditional PID. Additionally PDF works better in critical damping conditions while PID system tend to be underdamped. The separation of the control loops results in higher values for the "proportional" (gain), now the pseudoderivative, parameter when compared to PID controls. For a second order controlled systems the introduction of a derivative component in the PDF algorithm would introduce a still higher level of stability. This algorithm was designated by Phelan [6] as "PDF+".

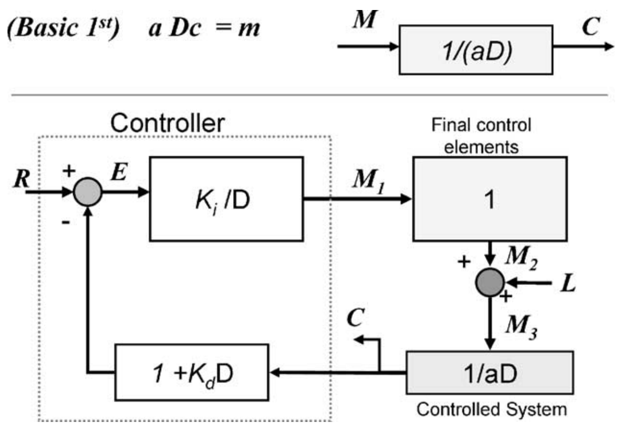


Fig. 6. Traditional controller loop for a First order controlled system. The differentiation is followed by integration and parameters K_d and K_i are in the same loop.

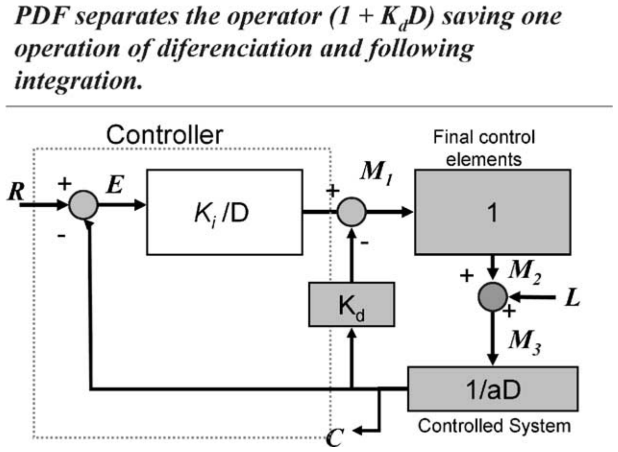
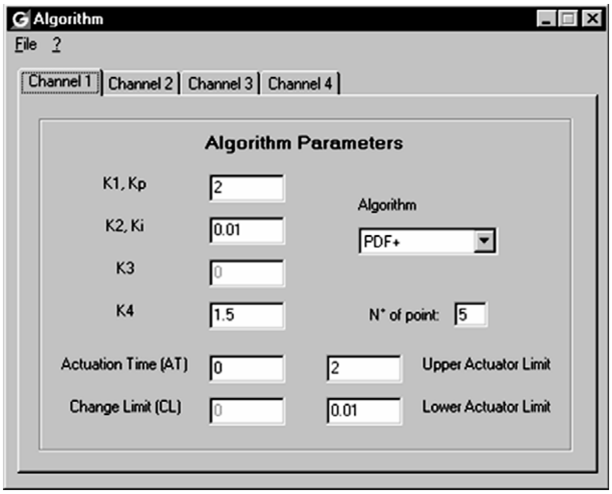


Fig. 7. PDF controller for a First order controlled system as defined by Richard Phelan. There are 2 independent loops each with one parameter for optimisation.

4. Multichannel controller

4.1. The speedflo unit

For certain systems, due to the large size or the degree of control required, an adequate control of the quality of the film can only be achieved when using several



K1, Kp: 2
K2, Ki: 0.01
K3: 0
K4: 1.5
Algorithm: PDF+
N° of point: 5
Actuation Time (AT): 0
Change Limit (CL): 0
Upper Actuator Limit: 2
Lower Actuator Limit: 0.01

Fig. 8. Multichannel algorithm control panel/window. Algorithm parameters can be set for each channel in order to integrate the interaction of all 4 channels.

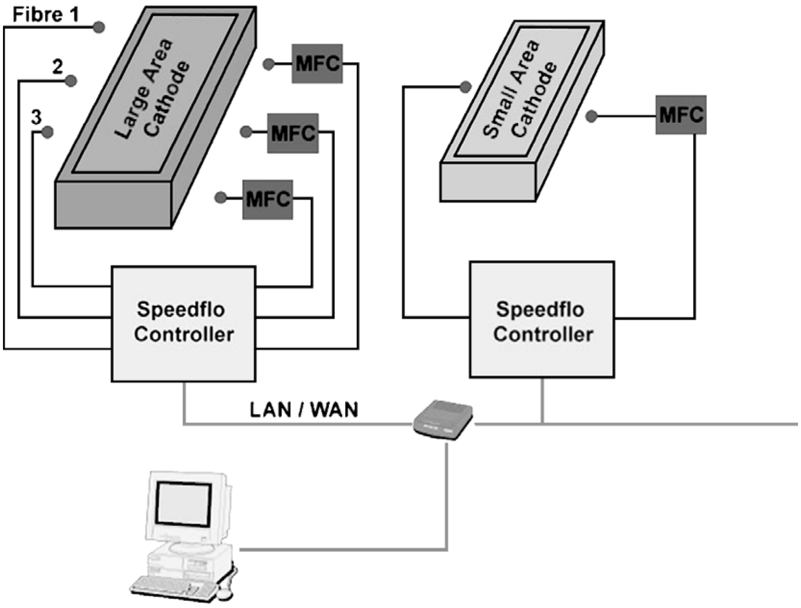


Fig. 9. Multichannel algorithm control panel/window. Algorithm parameters could be set for each channel in order to integrate the interaction of all 4 channels.

channels of reactive gas injection. For optimum operation these channels have to combine a degree of dependency and a degree of independency. The use of PDF algorithm allows setting a number of channels with that kind of flexibility of interaction. For this purpose a 4-channel version of a reactive gas controller has been developed under the commercial name of “speedflo”. A representation of the algorithm control panel/window could be seen in Fig. 8.

Speedflo can be used as a single channel controller, as individual multichannel controller, or as interdependent multichannel controller. The time response of the algorithm and actuation times of gas injection to the process are in the range of 10 ms which is needed for controlling the most difficult processes. Fig. 9 shows a network layout of possible operation modes of the speedflo unit.

5. Results

5.1. Speedflo control

Speedflo has been tested for the reactive sputtering and control of the several types of coatings, such as DLCs, CrN, CrO_x, AlO_x, SiO_x, AlN, SiN_x.TiO_x, NbO_x,. . .for planar, cylindrical rotatable, Full Face Erosion (moving magnets), Dual MF reactive sputtering,. . .and it has demonstrated that very good control of the process was possible in all cases (Table 1).

It is possible to see some of these examples in the following figures:

Fig. 10 shows a hysteresis test on a dual rotatable cylindrical Si targets (34" and 11.3 KW power). These tests serve to set up some of the initial parameters for the necessary control of the process. One of the most important aspects is the normalisation of the data so results become more meaningful and transferable to other systems. The hysteresis curve of Fig. 10 shows that control was possible via "PLASMA EMISSION MONITORING“ also called ”OPTICAL EMISSION MONITORING“ or via ”VOLTAGE" control. Fig. 11, shows a VOLTAGE control deposition run in which the setpoint value was varied from 35% to 15% and then to 18% of the values (note: 0% is fully poisoned — not zero plasma). This graph also shows how the Optical Emission Intensity changes during process and how when the glasses substrates pass in front of the plasma area there are shifts of plasma which affect the intensity reading.

Fig. 12 shows an example of reactive sputtering control of a Al target during AlN deposition. The control in this case was of the target voltage. As it can be seen there is a significative target conditioning on the Al target which means that when using OEM control there would be a certain period for which the target has to go through some strange conditioning, which generally involves generally the target “overpoisoning”. Target voltage control however is physically possible within 5 s of switch on of the gas controller.

The high speed of control and stability of the controller allows high rates of deposition relative to the pure metal

Table 1
Comparative experimental reactive deposition rates

Coating material type	Reactive deposition rate relative to metal rate
SiO_2	50%
TiO_2	35%
Si_3N_4	45%

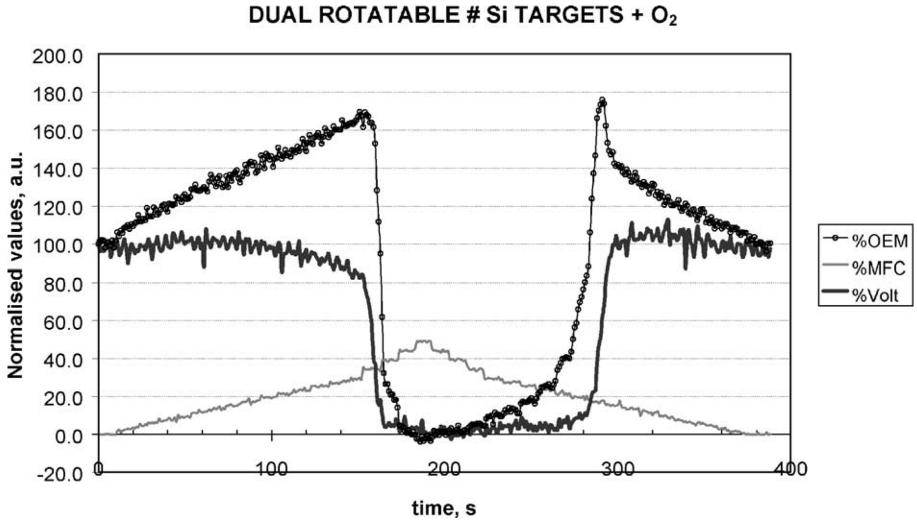


Fig. 10. Hysteresis test for dual rotatable AC (15 KHz) reactive sputtering. Target material: Si, reactive gas: O_2. Data are normalised so the reference could be extrapolated to other systems.

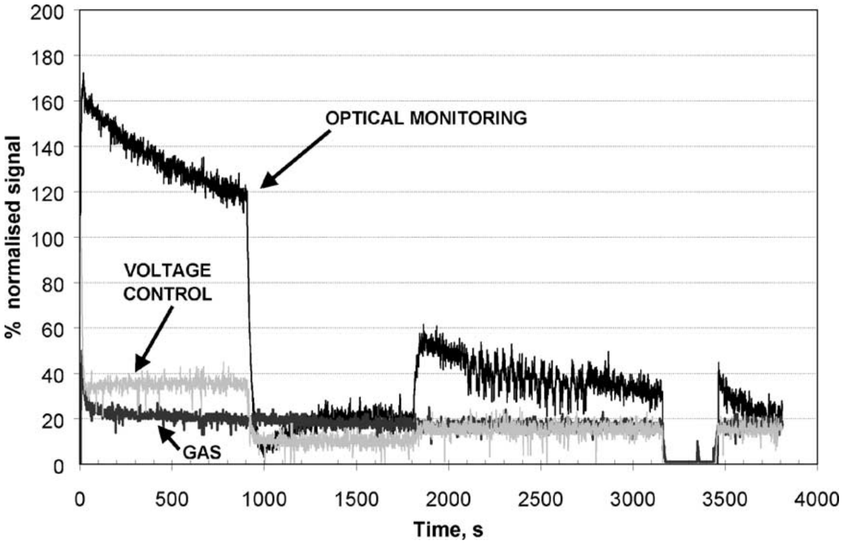


Fig. 11. Dual rotatable AC (15 KHz) reactive sputtering process run (Si+O_2). The control is in VOLTAGE of the targets. Optical Emission is being monitored.

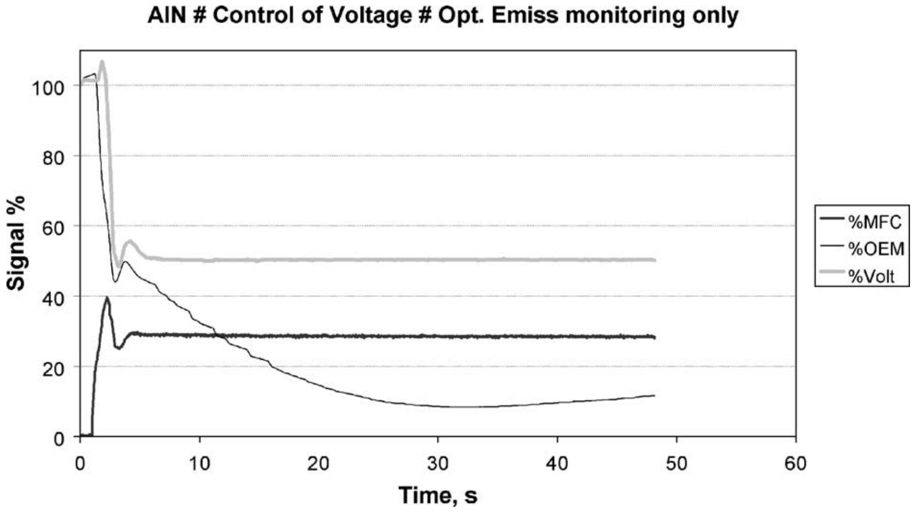


Fig. 12. Planar pulsed AlN reactive process control. This representation shows target VOLTAGE control. Optical emission control is also possible however the first minute of the process requires target conditioning (see OEM signal).

rates. The table below illustrates the relative rates for common materials in typical production scaled machines.

6. Conclusion

An advanced multichannel reactive plasma gas control system has been presented. The new controller offers both high-speed gas control combined with a very flexible control structure. The controller uses plasma emission monitoring, target voltage or any process sensor monitoring as the input into a high-speed control algorithm for gas input. The control algorithm and parameters can be tuned to different process requirements in order to optimize response times. PDF algorithm control has been successful in the control of complex systems such as those involving Si and Al using O_2 as reactive gas.

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