Flexible Gas Control for Reactive Magnetron Sputtering Process

V. Bellido-González, B. Daniel, J. Counsell, D. Monaghan
Gencoa Ltd, Liverpool,UK

Abstract

Most industrial plasma processes are dependent 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. 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 multi-channel 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.

A range of different industrial process types are illustrated and the corresponding ‘hysteresis’ behaviour. The demands for the control of the different systems and the types of sensors that are most useful is

1. Introduction

A basic model of a reactive magnetron sputtering process was described by Berg et al. [1-3] back in the late 1980s. The basic mass balance of the reactive gas gives the first principles of how to control this process (see Figure 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 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.

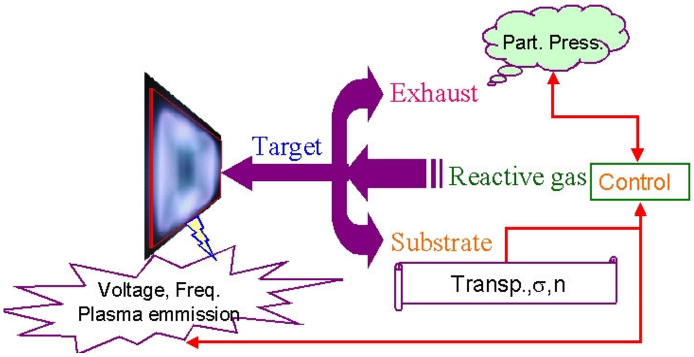


Fig. 1. Basic reactive sputtering model and control option

2. Modelling 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. The user of the automatic control system will input a reference value (*r*) which would represent a kind of response expected from the system (e.g. the temperature of a room). The controller would have an algorithm which would send some manipulated variable (m_1) to the control elements (for example a heater). The final control elements will give a new manipulated variable (m_2) (for example heat). That would combine with other loads (*l*) from the system (for example sun or human heat) which are not manipulated giving us an overall manipulated variable of the reaction m_3. Now there is a way of monitoring what the reaction is (for example measuring the temperature in the room), and that will give us what we call the controlled variable value *c*. This value c is fed back to the controller which will compare it with the reference value (*r*) and based on the error e will act consequently in the control loop.

As a general guide for the rest of the discussion the following definitions will be adopted:

r= reference input

c= controlled variable

e= ***r***-***c*** , which is the error (opposite to the general concept of error)

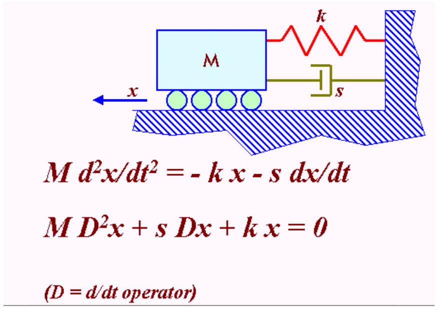


Fig. 3. The basic damped harmonic system.

$\boldsymbol{m_n}$= manupilated variable or measure

l= load

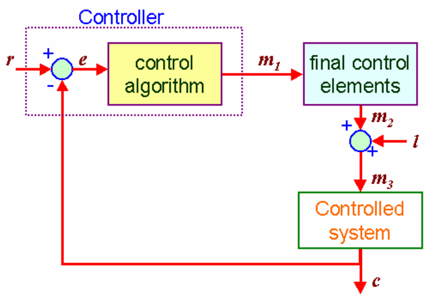


Fig. 2. The basic automatic control system described using block diagrams.

2.2 Damped simple harmonic motion

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).

So the "movement" equation for this damped harmonic system could be described as;

$$MD^2x + s\,Dx + kx = 0 \qquad (1)$$

where

M is the mass

D is the differential operator

$$D = d/dt \qquad (2)$$

x is the "space" variable

k is the spring constant

s is the stiffness.

(if D is the differential operator, then the inverse $1/D$ will denote the Integration)

2.3 Forced oscillator

When an external force, F, is applied to this system then the overall equation will become:

$$MD^2x + s\,Dx + kx = F \tag{3}$$

This model introduces two concepts:

1.- Critical damping, for which in a set of conditions it will possible to arrive from position A to position B in the minimum time.

2.- Resonance, for which the delivery of energy is optimum

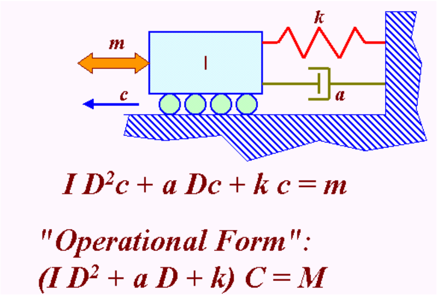


Fig. 4. Operational form for a forced oscillator (2nd order controller).

By applying the nomemclature 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:

$$ID^2c + a\,Dc + kc = m \tag{4}$$

which in operational form will be:

$$(ID^2 + a\,D + k)\,C = M \tag{5}$$

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

a) Zero-th order controlled system

b) First order controlled system

c) Second order controlled system

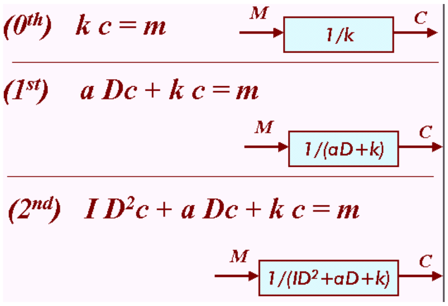


Fig. 5. Different orders of controlled system and operational relationship between the manipulated operation *M* and the response of the controlled variable *C*.

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 Figure 6. First order controlled systems tend to be more difficult to control than a Second order one. In the traditional way of the controller at least two of the parameteres of the algorithm will be involved in the same loop. This would make generally optimisation more difficult than having parameters in separate loop levels.

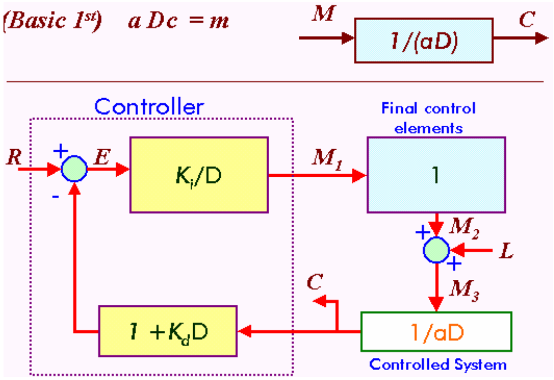


Fig. 6. Traditional controller loop for a First order controlled system. The differentiation is followed by integration and parameters K_d and K_i are in the same loop.

3.2 The PDF algorithm

More than 30 years ago Richard Phelan [5-6] 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 Figure 6 the transformation which is fed back to the controller could be divided into two parts, the part that contains the derivative (K_dD) 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 Figure 7. This would be a "pseudoderivative" route, therefore the name Pseudo-Derivative Feedback (PDF) control.

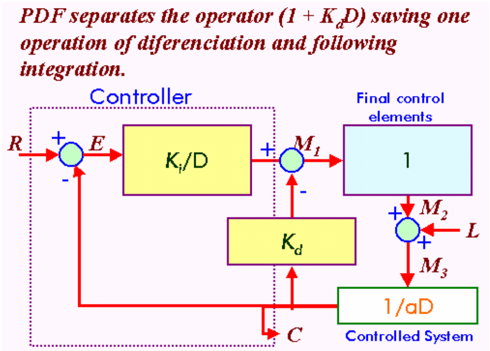


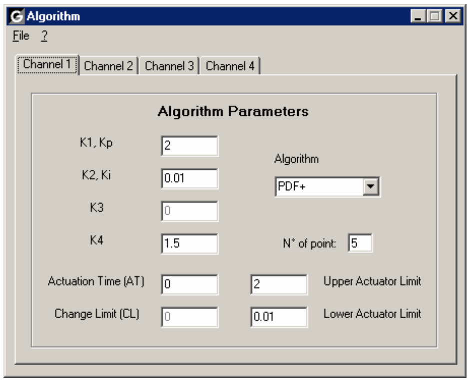
Fig. 7. PDF controller for a First order controlled sytem as defined by Richard Phelan. There are 2 independent loops each with one parameter for optimisation.

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+".

4. MULTICHANNEL CONTROLLER

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 channels of reactive gas injection. For optimum operation these channels have to combine a degree of dependency and a degree of interdependency. 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 Figure 8.



Algorithm Parameters

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

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

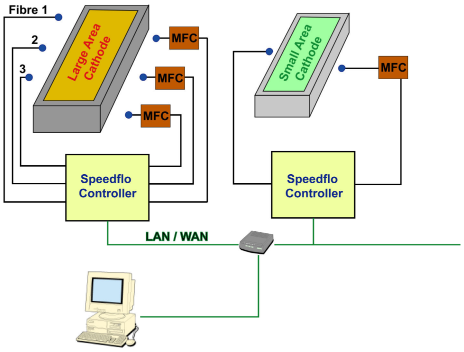


Fig. 9. Multi-channel algorithm control panel/window. Algorithm parameters could be set for each channel in order to integrate the interaction of all 4 channels.

5. RESULTS

Speedflo control

Speedflo has been tested for the reactive sputtering and control of the several types of coatings, such as DLCs, CrN, CrOx, AlOx, SiOx, AlN, SiNx.TiOx, NbOx,... 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.

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

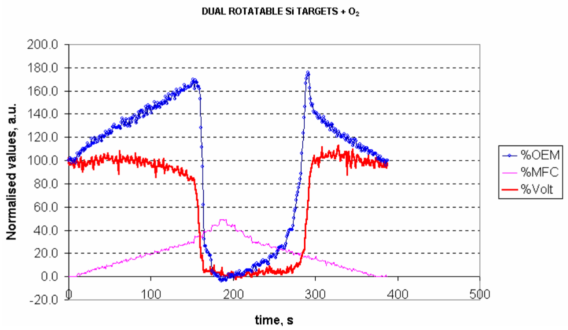


Fig. 10. Hysterisis test for dual rotatable AC (15 KHz) reactive sputtering. Taget material Si. reactive gas: O_2. Data are normalised so the reference could be extrapolated to other systems.

In order to understand the limitations of the plasma environment it is useful to perform what is termed a ‘hysterisis test’. The speedflo simply increases the gas flow step-wise and then decreases. The maximum gas input in the cycle should be enough to fully poison the target. As the gas flow is adjusted the target voltage and plasma emission signals can be monitored. By examining this data it is possible to determine which is the best mode of control (voltage and / or PEM) and also the possible range of control in terms of gas flow.

Figure 10 shows a hysterisis 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 hysterisis curve of Figure 10 shows that control was possible via "PLASMA EMISSION MONITORING" also called "OPTICAL EMISSION MONITORING" or via "VOLTAGE" control. Figure 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.

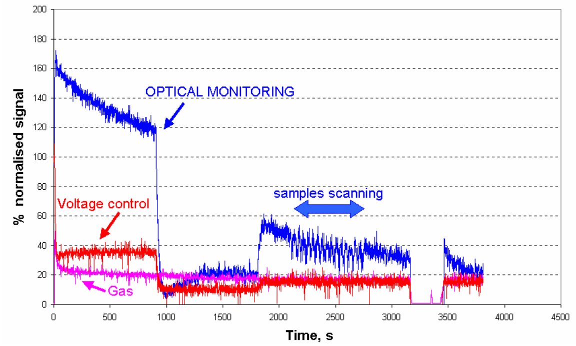


Fig. 11. Dual rotatable AC (15 KHz) reactive sputtering process run (Si + O_2). The control is in VOLTAGE of the targets. Optical Emission is being monitored.

Plasma / Process Drift Problems

Although the successful reactive process control is achievable in many instances, some material systems can be subject to a plasma ‘drift’ with time. Hence this process must be understood and philosophies must be adopt that the control system can introduce to provide reliable long term control.

This phenomenon can be a shorter drift as a result of initial target conditioning.

Figure 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 significant 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 conditioning, which generally involves generally the target "over-poisoning". Target voltage control however is physically possible within 5 seconds of switch on of the gas controller.

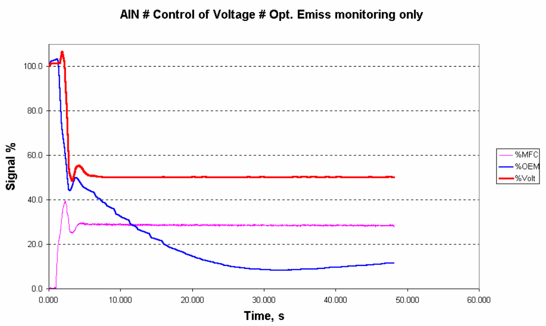
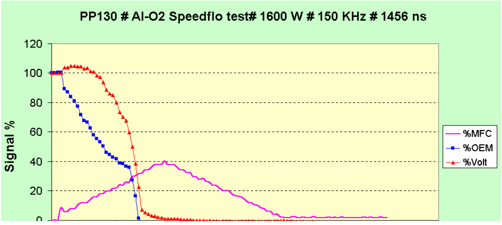


Fig. 12. planar pulsed AlN reactive process control. This representation shows target VOLTAGE control. Optical emission control is also possible however the first minute of the process requires target conditioning (see OEM signal).

Figure 13 shows a short term target pre-conditioning for aluminium sputtered reactively with oxygen. The target voltage responds in the expected manner as the oxygen is increase, however the plasma emission signal exhibits a time lag until after 25 seconds it assumes the usually response with the increasing oxygen flow. This is due to the sub-implantation of oxygen into the metal target during the early stages of reactive sputtering with a ‘clean’ target not previously reactively sputtered.



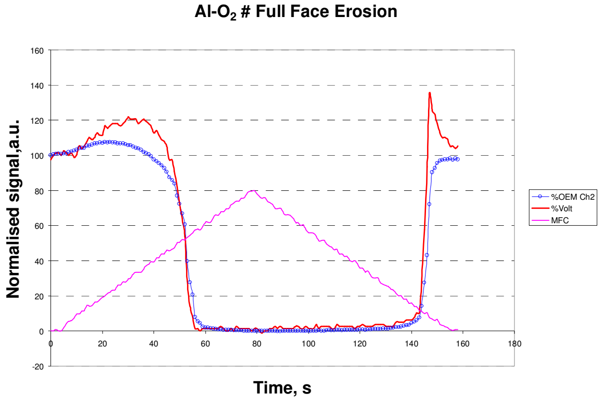


Fig. 13. Short term target conditioning for Al + O2 system due to sub-implantation of oxygen.

Figure 14 in comparison for the same Aluminium and Metal system does not exhibit the same initial plasma emission lag as the target was in a pre-conditioned state proir to the introduction of the oxygen.

Fig. 14. Reactive sputtering hysterisis response in Al + O2 system by a circular Full Face Erosion (FFE) type magnetron (rotating magnets).

Some process changes can be over an extended period of time such as illustrated in Figure 15 which is the Indium Tin Oxide systems in a reactive oxygen environment. As can be seen under plasma emission control the signal is held constant, but the oxygen requirement is receasing and there is a corresponding increase in the target voltage. As the power on the target is ramped down the oxygen requirements drops more quickly at the same time as the voltage increases more rapidly even though the speedflo system is still maintaining the PEM setpoint perfectly. As the controller is switched off, the target poisons fully (0% emission) and the target voltage starts to recover.

This drift could be avoided by running the power supply in current mode instead of power control as with the illustrated example. When in power mode a rise in target voltage will result in a corresponding decrease in current. In most cases the current is more important from a sputtering rate point of view that the voltage. So a current reduction is reducing the sputter rate and hence less oxygen is need. The situation is self-propogating and exagerates the plasma drift. By runnning in current mode the rates will be maintained better and drift will be reduced or eliminated.

Speed of Response

The high speed of control and stability of the controller allows high rates of deposition relative to the pure metal rates. The following table illustrates the relative rates for common materials in typical production scaled machines.

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	46%

6. Conclusion

An advanced multi-channel 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 succesful in the control of complex systems such as those involving Si and Al using O_2 as reactive gas.

Acknowledgements

The authors would like to acknowledge the following people and organizations for their contributions to this paper .

- Anja Blondeel (Bekaert VDS N.V., Deinze, Belgium) for the tests carried out at their R&D facility with dual rotatable magnetrons.
- Masato Yoshikawa (Bridgestone, Tokyo, Japan) for the analysis of deposited TiO_2, SiO_2 & Si_3N_4 coatings.
- European Commission for their financial support in EFCAP, COMING-DRY and OPTIMERECELL projects.

Also the authors would like to thank other contributors which preferred not to be mentioned. Nevertheless they agree for their test data to be published and we thank them for that.

References

[1] S. Berg, H-O, Blom, T. Larsson, and C. Nender, J.Vac.Sci.Technol., A5 (2) (1987) 202.

[2] T. Larsson, H-O. Blom, C. Nender, and S. Berg, J. Vac. Sci. Technol., A6 (3) (1988) 1832.

[3] S. Berg, T. Larsson, C. Nender, and HO. Blom, J. Appl. Phys. 63(3) (1988) 887

[4] S.J. Nadel, P. Greene, “High rate sputtering technology for throughput and quality”, International Glass Review, Issue 3, 2001, p. 45.

[5] R.M. Phelan, Pseudo-Derivative-Feedback (PDF) Control, UCRL-51036, University of California, Laurence Livermore Laboratory 1971

[6] R.M. Phelan, Automatic Control Systems, 1st ed., Cornell University Press, Ithaca and London, 1977