

Long-Term Process Control and Stability in Reactive Sputtering

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ABSTRACT

The creation of layers by reactive sputtering is now commonplace in a wide number of industry sectors. Reactive sputtering has advantages of speed of deposition and lower capital equipment cost when compared to RF sputtering from compound targets. Reactive deposition involves mixing a gas with the sputtered species. There is a large body of work illustrating the instability or “hysteresis” that this reactive type of process creates [1,2]. In order to maintain the highest deposition rates, a feedback control system is required to keep the appropriate balance of sputtered atoms to reactive gas. If this is performed correctly, then rates as high as 50% of the pure metal rate can be realized for reactive compound formation [3]. The inherent instability of the reactive sputtering process is further compounded by short-term and long-term drifts or changes that can commonly occur as a result of machine or process complications. In order to guarantee both high rates and long term stability, a complex feedback control solution is required that has high speed responses with hardware and software features to combat changes that can occur in the plasma environment. This paper will illustrate an advanced and integrated solution to provide the degree of control required for such processes.

REACTIVE SPUTTERING MODEL

A basic model of a reactive magnetron sputtering process was described by Berg et al. [4-6] back in the late 1980s. The basic mass balance of the reactive gas gives the first principles of how to control this process. 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, a second part 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 implement a closed loop control system around this process, at least one input from the process is required. Also, one output that can manipulate the process in the direction of the desired set-point at the required speed. There are a range of inputs/outputs that can be considered for such processes, see Figure 1.

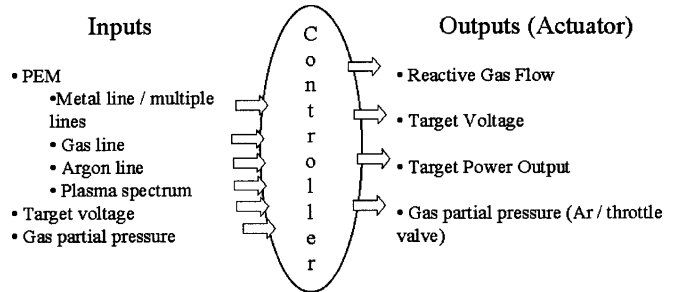


Figure 1. Inputs and outputs from a typical reactive sputtering process.

The choice of input will depend upon the process specifics. For example target voltage feedback is suitable for materials such as Al_2O_3 , AlN, SiO_2 , and Si_3N_4 since there is a simple and large response in the target voltage as the gas is introduced. In other material systems, such as titanium and oxygen shown in Figure 2, unlike the plasma emission signal, the voltage response follows a non-monotonous response in the area of interest, thus making it less easy to control (although still possible by limiting the controlling zone). The behavior of target voltage will be determined by the electrical properties of the compounds formed on the target surface. The formation of such compounds will be a result of the chemistry of the target material and the reactive gas. This can be complex and several different compounds may form at different stages, each with different electrical properties. Hence the material combinations will be responsible for the electrical response from the system and whether the target voltage can be used for the feedback control.

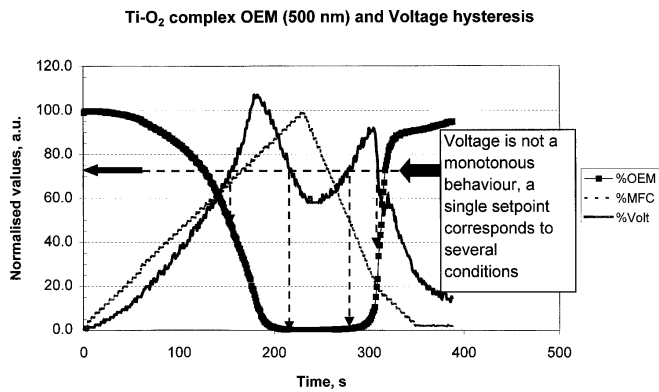


Figure 2. Variation in target voltage and optical emission intensity with changes in the oxygen input when sputtering Titanium. Note: signals have been normalized using 100% for no reactive gas present, and 0% for the fully poisoned state.

For large area process, target voltage alone is usually not the best solution, as the signal is representative of the whole target area and zonal control is commonly needed to achieve a good uniformity across a large area. The most universal process input method is from the optical emission monitoring of the plasma (OEM), see Figures 3 and 4. It has the advantage of being very sensitive and high speed. One disadvantage is that the fiber-optics can become coated and the signal can reduce with time. Hence, methods such as using a collimated tube and passing argon gas in front of the window are required to eliminate such problems.

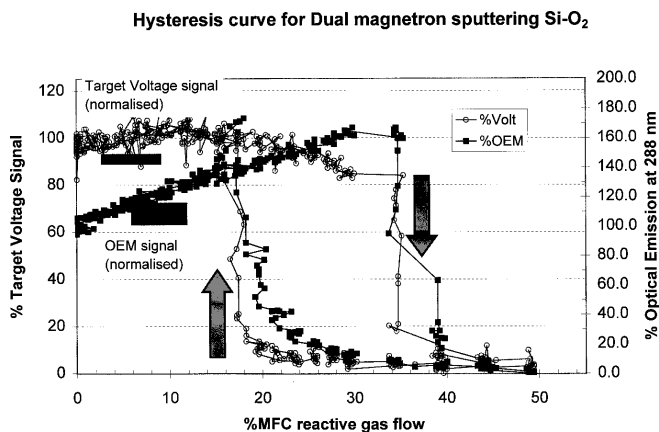


Figure 3. Hysteresis curves for dual Si targets (rotatable) displayed in the “classical” way with signal (OEM or voltage) plotted with respect to reactive gas flow.

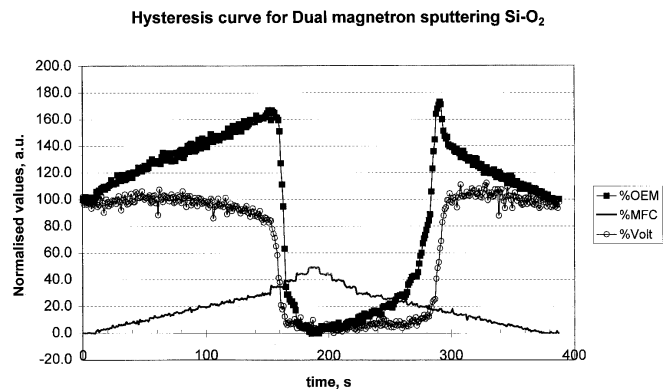


Figure 4. Hysteresis curves for dual Si targets (rotatable) displayed in the preferred style of the authors with signal (OEM or voltage) plotted with respect to time during a reactive gas ramp-up and ramp-down.

From a process control point of view, the types of coatings and rates obtained could be very different when working at different points within the hysteresis curve. When such phenomena appear, the speed of response needs to be adequate or the target could move very quickly into a different mode, as Figure 8 indicates. In certain sputtering power and pulse conditions, the target could poison and remain poison for a long time before the control could be re-established. In this case, the variation in coating deposition rate varies more than 20 times, change that is obviously very undesirable. As the changes in reactive gas demand could vary dramatically and a fast actuation time is needed in order to keep the process under stable conditions. Figure 5 shows an example for Aluminium target showing the dramatic change of Aluminium spectral signal (400 nm filter) for a small difference in the gas delivery ramp.

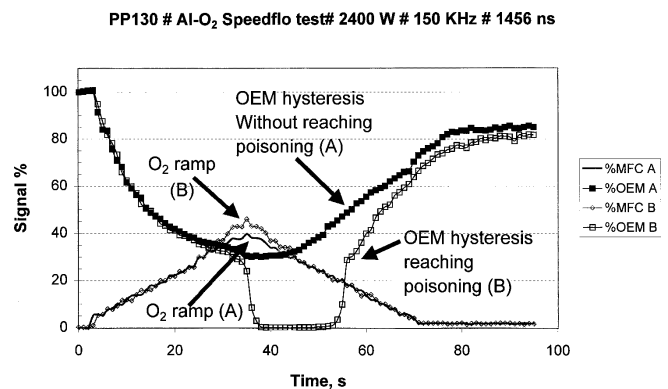


Figure 5. Dramatic change in Aluminium sputtering (measured as Aluminium signal at 400 nm filter) for a small variation on reactive gas (O_2) ramp.

This type of response demonstrates the need for an adequate selection of process conditions where the responses are implemented within the time frame that allows the system to be considered as “stable”. The limitations in a real system to deliver energy or change in a particular way can restrict the process parameters to a particular range.

HIGH SPEED CLOSED LOOP CONTROL

The feedback control solution for most industrial processes are mainly based upon PID. This is a well documented mode of control and many forms of this type of controller exist. In developing the control architecture for reactive sputter process, a less common type of control has been found to offer many advantages over conventional PID methods [3]. This alternative controller is called pseudo derivative feedback control or PDF. PDF was reported by Phelan in the 1970's [7,8] and a modified version of that control principle has been used to speed-up the response that can be gained from reactive gas process control. Basically, PDF has similar control capabilities when compared to PID, but it has a bigger “engine” and stronger “brakes”. The reason behind this lies in that fact that typically PID solutions are “under-damped”, whereas PDF allows easier “critical damping”. This means that it can more rapidly attain the set-point and apply the brakes more aggressively should the need arise. PDF is also more tolerant of spurious loads and is hence more stable and easier to work with in general but in particular in a multi-channel arrangement which is typically required for large area coating.

PROCESS DRIFTS AND INSTABILITIES

In working with real process control situations, it becomes apparent that not only is a fast feedback method required to keep the process under tight control, but also the ability to deal with changes that occur over both short or long timeframes. There are many reasons for such changes, and it's almost certain that changes will occur. The change may be a result of multiple combinations of factors, which makes it hard to predict and the responses complex. Some of the possible reasons for changes are as follows:

- Target erosion - change in position of the target surface relative to a PEM sensor.
- Anode and chamber becomes covered in insulating material causing plasma drift.
- Heating of shields and fixtures producing expansion and change in sensor position.
- Change in electrical property of target surface causing plasma expansion or contraction.
- Substrate motion in front of the plasma and different substrate (glass) sizes.

- Leaks in the vacuum chamber.
- Moisture liberation from the substrate during the coating process.
- Gradual coating of PEM sensor.
- Target “conditioning” at the start of operation.
- Motion of the plasma - moving magnetics.
- Co-sputtering of materials leading to cross target contamination.
- Use of two reactive gases - gradual domination of one gas or material system over another.

Thus in reality, a successful control solution requires the ability to “tune” out all the possible process changes and produce the same films reproducibly with time. To achieve this, more than one single input from the process is required in order to produce a fuller picture of the environment and to handle these complications.

MULTI-FUNCTIONAL REACTIVE SPUTTER GAS CONTROLLER

The use of multiple inputs and/or outputs provides a much more intelligent system for providing better control. For example, the monitoring of both the metal plasma emission line and the argon gas line, and then controlling around a ratio of the two signals, can eliminate some of the drifts associated with target erosion, plasma shifts/substrate motion. If the target voltage is further used as an input or output, then changes in plasma impedance can be accounted for. As well as using the physical hardware features, software tricks can be played where the input signal is averaged over a longer timeframe to “filter” out short term changes and disturbances. In the same way, varying the sampling rate can, when combined with the averaging of the signal, be used to “tune” out short term variations.

So the ideal controller has the ability and flexibility to handle multiple I/O's in an appropriate time frame in order to provide a more robust control solution. The software then can pre-process that data to further enhance system stability.

FEEDBACK CONTROL OF MAGNETRON CATHODES WITH MOVING MAGNETIC ARRAYS

An example of an extreme case of short-term plasma variation is where the magnetic array rotates and scans the plasma over a target surface. This type of device is commonly used in cluster tools for the micro-electronics industry. As the plasma moves constantly over the target surface, the intensity of plasma emission from the target area at any point is changing at the same frequency.

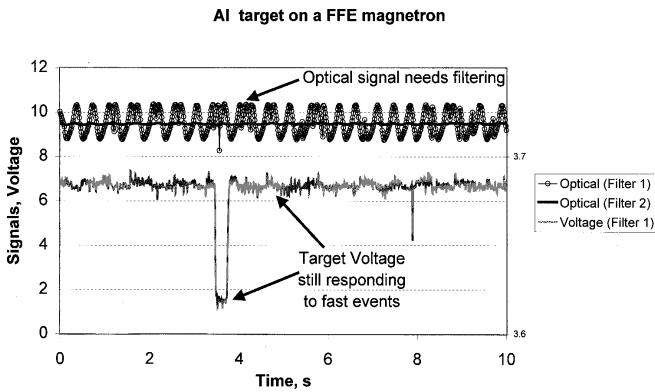


Figure 6. Variation in OEM and Target Voltage with time for a “full-face erosion” magnetron source with a scanning plasma over the target surface. Filtered and unfiltered.

If target voltage feedback is used, then the target voltage is less affected by the moving magnetics. However, this can only be used for certain materials and there will still be a shift in voltage as the target erodes.

If plasma emission is used, then there will be a large change in signal with time. To reduce the variation, one or a combination of the following three techniques can be used:

- Ratio of the metal intensity with the argon intensity.
- Use of an electronic filter for the input signal.
- ‘Smoothing’ of the data by taking an average of several points.

By taking a ratio of the metal emission to the argon emission, long- and short-term variations in signal can be eliminated to a large degree. The use of an electronic filter can also be used on either the metal and/or the argon signal. Further, an average or “smoothing” can then be taken over a number of points over a relatively short time (msec). The use of these three methods can give a very stable input to the controller regardless of the process variations, see Figure 3. Depending upon the nature of the variations, 1, 2 or all 3 methods can be used in combination to combat change. It is important that the process control software and interface is flexible enough to handle these varying requirements. Also, the controller requires the capacity for a number of input and outputs in order to handle the different signals and also to maintain processing speed for rapid data calculations. With some of the methods, there will be a trade-off with the reaction time of the gas going into the process. If the speed of the gas input to the process is slowed to a level where the process control is lost, then the data treatment delay has to be adjusted to bring it back into control.

As mentioned already, reactive processes could be very complicated in terms of what kind of surface transformation is taking place at the target surface. For example, oxides of different nature could be formed on the target surface as it happens with Ti and Indium Tin Oxide (Figure 7). In the case

of Titanium, the target voltage variation on its own is not an adequate signal for control as it doesn’t present a monotonous behavior. In the case of ITO it highlights the difficulty in maintaining a stable process for very long periods. Generally, this material suffers from nodule formation [9]. In current production standards conditions, neither constant power, constant O_2 concentration, or constant optical emission would give a stable process. In order to control and limit the surface transformation there has been two areas of improvement. One is increasing the magnetic field in order to decrease the sputtering voltage and limiting the target damage/transformation by ion bombardment. A second one has been the sputtering of ITO using very hot targets ($Temp > 300^\circ C$) in order to control phase transformation.

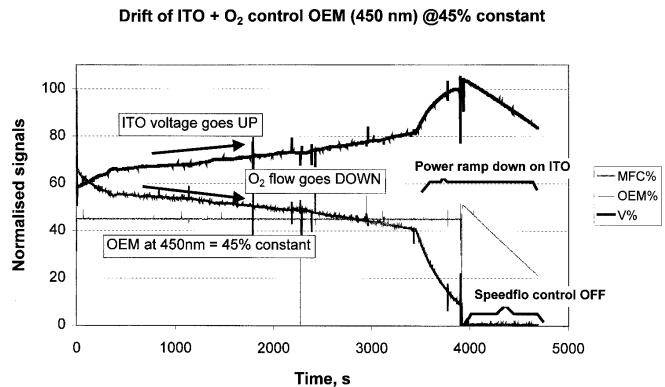


Figure 7. ITO targets present a very complicated plasma chemistry. There is a transformation of the surface which results in a more insulating compound being formed. Therefore the target impedance changes. When controlling the Optical emission of In (450 nm) at a constant power the demand of oxygen decreases, the target voltage increases, and the more energetic particle impact forces the target to become more insulating.

SPEEDFLO CONTROLLER

Gencoa has developed a control system called Speedflo, which combines a number of I/O’s (4 or optionally 8) with a flexible software platform for handling the data and to provide stability. Speed of process control is provided by using the PDF algorithm in combination with a fast processing time (typically 2.5msec). The controller can work in a single or multi-channel mode, as is required on large area cathodes with 3 to 5 monitoring/control zones. Built-in process control algorithms can tune to varying process and machine conditions by means of adjustment of one or more of the “gains” in the control software interface. Other software features include a complex layer facility where the gas control setting can be constantly varied to produce multi-layer or graded coating structures, as well as serving to find the appropriate algorithm parameters needed for the control.

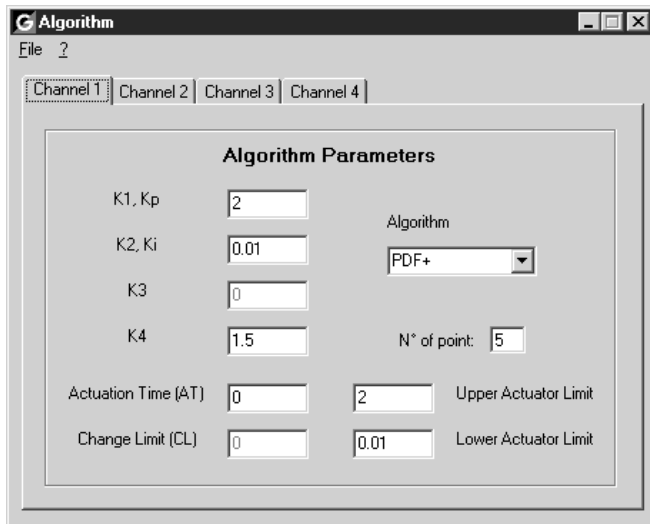


Figure 8. Screen shot of the algorithm parameter setting sub-window from the Speedflo software system.

CONCLUSIONS

Reactive sputter processes are inherently unstable and require fast feedback control. In addition, the process can display changes over short and long timescales for a wide variety of reasons. In order to ensure both effective gas control and stability with time, multiple inputs are required to the controller in order to process the data and filter out the causes of movement away from the setpoint.

REFERENCES

1. J. Chapin and C.R. Condon, US Patent 4,166,784 (1979).
2. S.J. Nadel and P. Greene, "High rate sputtering technology for throughput and quality", *International Glass Review*, Issue 3, 2001, p. 45.
3. V. Bellido-González, B. Daniel, J. Counsell, and D. Monaghan, "Reactive Gas Control of Non Stable Plasma Conditions", Proc of ICCG, Saarbrueken, 2004.
4. S. Berg, H.-O., Blom, T. Larsson, and C. Nender, *J.Vac.Sci.Technol.*, A5 (2) (1987) 202.
5. T. Larsson, H.-O. Blom, C. Nender, and S. Berg, *J. Vac. Sci. Technol.*, A6 (3) (1988) 1832.
6. S. Berg, T. Larsson, C. Nender, and H.-O. Blom, *J. Appl. Phys.* 63(3) (1988) 887.
7. R.M. Phelan, Pseudo-Derivative-Feedback (PDF) Control, UCRL-51036, University of California, Lawrence Livermore Laboratory 1971.
8. R.M. Phelan, *Automatic Control Systems*, 1st ed., Cornell University Press, Ithaca and London, 1977.
9. B.G. Lewis and D.C. Paine, "Applications and Processing of Transparent Conductive Oxides", *MRS Bulletin* page 22 August (2000).