Making Magnetron Sputtering Work: Modelling Reactive Sputtering Dynamics, Part 3
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It is highly advantageous to understand the dynamics of a representative large-scale reactive sputtering process, particularly when operating in the transition mode between the metallic state (with only a small fraction covered with compound) and the poisoned state (approaching unity coverage with compound) of the target. A static model can be used to find the equilibrium characteristics of the process. Then analysis of a linearized model can provide insight into the dynamics at a particular operating point. When reactive sputtering processes are operated in the naturally unstable transition region, where the slope of the reactive gas pressure versus flow curve reverses, they must be stabilized with output feedback control to permit stable operation. Published data can be used to construct a model of a representative large-area reactive sputtering process, as used in industrial glass coaters. Linear analysis of the linearized model can provide insight into open and closed loop dynamics and stability. Simulations can provide insight into the relationship between arc response shutdown time and process stability. This article addresses the simulation of such a system using a dynamical model, with a stabilizing controller to allow simulation of operation in the transition region, including assessment of required arc response time and example means to achieve it.

Introduction
In Part 1 of this series, I showed the development of the equations for the dynamical version of the Berg Model [1]. Part 2 showed linearization of the model, and use of linear analysis tools to gain insight into dynamics and stability; one way to design a stabilizing controller was shown and used in the example analysis [2]. That controller will also be used in the simulations described in this article.

A closed loop system using state feedback, as developed in Part 2 [2], is shown in Figure 1. The system in Figure 1 has provisions for insertion of a set point, \( x_{op} \), and the operating point for the state, \( u_{op} \). This feedback system structure lends itself to use of the Linear Quadratic Regulator (LQR) approach for the controller design [2]. The LQR technique offers some guarantees of stability and performance; in general it produces controllers which are well behaved. The approach requires that all states be available for feedback, because it (LQR) generates a three element state feedback gain row vector \( k \) which is shown in Equation (1) below. In this case there is only partial state feedback available since coverage fraction measurements are not (yet) practical. Design of the controller started with the state feedback vector \( k \)

\[
k = \begin{bmatrix} k_1 & k_2 & k_3 \end{bmatrix}
\]  

(1)

generated by LQR, then elements \( k_1 \) and \( k_3 \) were set to zero since target coverage and chamber coverage states are not available as measurements. Then \( k_2 \), corresponding to partial pressure, was used as a starting point for gain for partial pressure feedback. To provide adequate robustness, eigenvalues of the closed loop system were evaluated for a range of \( k_1 \) values. Then a value \( k_1 \) was chosen for sufficient margin to ensure stability. The result is a system which controls partial pressure [2].

After arriving at a starting point for \( k_1 \), as described above, the closed loop eigenvalues were plotted, varying \( k_1 \) as a parameter. The locus of the complex eigenvalues of the (linearized) system is shown in Figure 2. This plot shows that one eigenvalue has a positive real part at the starting point, but that it becomes negative as \( k_1 \) is increased, resulting in a stable system.

In order to demonstrate linear analysis of a reactive sputtering system, a system for which data are published was studied [6]. Model parameters were chosen to be representative of a large area, mid-frequency dual magnetron coating process with magnetrons 2 meters long operating at about 120 kW. The operating point for simulations in the transition region was calculated by the static Berg Model, implemented in a spreadsheet [1]. Results are shown in Figure 3. The transition region is the...
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Arc Response Dynamics
One consideration of paramount importance is the stability of the reactive sputtering process. Stability can have broad meaning. There is on one hand the intrinsic stability, which often implies freedom from oscillation, or perhaps, the ability to stay within a bound-able neighborhood of a desired operating point. While this notion of stability is quite applicable, and important, to reactive sputtering processes, there is another notion of stability which must be also considered. Reactive sputtering processes are by their nature prone to arcing. The dielectric material which forms on the target surface in some processes is believed to accumulate electrical charge to the point where it breaks down and initiates an arc from the plasma to the target, where the glow discharge over much of the target surface collapses to a small diameter arc [3]. When an arc does occur, it must be handled by the system power supply. This typically entails an interruption in the power delivered to the process for some period of time. If power to the process is interrupted for long enough, it can move significantly away from its desired operating point, and take some time to return once the power is re-applied. When power is reapplied, the reactive gas pressure, target surface coverage, chamber surface coverage, electrical impedance and deposition rate will have changed.

It is clearly important to develop an understanding of these issues, analytically and numerically as well as empirically [4]. To fully realize the potential of reactive sputtering, it will be necessary to systematically develop an understanding based on reliable mathematical models which capture the essential physics of the process. This article addresses the issue by using a model-based approach to examine acceptable maximum power supply arc response shut down times for a representative industrial glass coating process.

Simulations were performed with Simulink® [5]. Results of
continued on page 40
simulations performed using this model highlight the need for rapid arc response and a managed low arc rate in practical industrial reactive sputtering processes. The results show partial pressure, target coverage fraction, chamber surfaces coverage fraction, and deposition rate as a function of time. Model parameters, listed in Table 1 in Part 2 [2], were chosen to be representative of a large area, mid-frequency dual magnetron coating process with magnetrons 2 meters long operating at about 120 kW [6].

Response of the process to a 20 msec arc shutdown is shown in Figure 4. The effect of the shutdown on the deposition rate lasts much longer than the shutdown time, and would likely result in visible “banding” on the product coated in an inline glass coater. The drop in rate is much larger than that which might be anticipated by simply looking at partial pressure or target coverage fraction. In fact, a small increase in target coverage fraction can result in a large drop in metal flux to the target because the compound sputters with a much lower yield than the target material. It seems unlikely that this process could be stabilized if shutdowns of this length occurred a few times a second.

Figure 5 shows normalized rate as a function of coverage fraction. Normalized rate is the effective target material sputtering yield, including both intrinsic target material and target material incorporated in compound at the target surface. The expression for normalized rate, $R_{\text{norm}}$, is

$$R_{\text{norm}} = (1 - \theta_t)S_M + \beta \theta_t S_C$$

(2)

where $\theta_t$ is the fraction of the target covered with compound, $S_M$ (atoms/ion) is the sputtering yield of the target material, $\beta$ is the number of metal atoms in the compound, and $S_C$ (atoms/ion) is the sputtering yield of the compound.

Both the equilibrium normalized rate and the normalized rate after a 20 msec shutdown are shown in Figure 5. The equilibrium coverage fraction is 0.76, with a normalized rate of 0.27. After a 20 msec shutdown, when power is reapplied, the coverage fraction is 0.90, with a normalized rate of 0.13. This explains why just a 20% increase in target coverage fraction can result in a 50% decrease in rate at the time when power is reapplied following an arc response shutdown.

It is also important to note that even if partial pressure could be held absolutely constant, the coverage fraction would increase, with a concomitant decrease in normalized rate.

A loss of rate may not be the only effect of a long shutdown for arc response. The average target surface coverage fraction also increases, as seen in Figure 4. This could result in a change of film properties as well. Experimental data for deposition of AlO$_x$ in the transition region shows that the index of refraction decreases from 1.66 to 1.61 as partial pressure is increased, while remaining in the transition region [7]. As partial pressure increases, target surface coverage fraction also increases, approaching unity. Therefore, it could be that longer shutdown times result in films with lower index of refraction, and perhaps reduced density.

Response of the process to a 5.0 msec arc shutdown is shown in Figure 6. Even a 5.0 msec shutdown results in a significant disturbance to the process, and it takes some time for the rate to recover to the pre-shutdown level.

Response of the process to a 1.0 msec arc response shutdown is shown in Figure 7. The longer term effect on rate is in the range of a few percent. An arc response shutdown on the order of 1.0 msec or less allows process operation to continue nearly seamlessly after power is restored.
process studied here. The result of longer shutdown times is a reduction of deposition rate. An additional effect of longer shutdown times may be a change in index of refraction of the films, owing to the increase in average target surface coverage fraction. Experimental data has shown that pulsed current source supplies optimized for large area mid-frequency dual magnetron sputtering processes can have shutdown times of 50 msec or less.

**References**


**Summary and Conclusions**

Process simulations showed that power supply arc response shutdowns need to be of order 1.0 msec or less to minimize disturbance to the large area transition mode reactive sputtering process studied here. The result of longer shutdown times is a reduction of deposition rate. An additional effect of longer shutdown times may be a change in index of refraction of the films, owing to the increase in average target surface coverage fraction. Experimental data has shown that pulsed current source supplies optimized for large area mid-frequency dual magnetron sputtering processes can have shutdown times of 50 msec or less.

**Arc Response Requirements**

In general, it is desirable to minimize the time the power supply shuts off in response to an arc. It is necessary to shut off long enough to extinguish the arc, but not so long that available deposition rate is wasted.

The simulation results in the previous section showed that a key requirement for stabilization of the deposition rate for processes operating in the transition region is a rapid arc response, less than 1 msec for the system studied.

Pulsed supplies for dual magnetron sputtering (DMS) have been developed starting in the mid-1990s [8-11]. Arc response from a recently developed mid-frequency pulsed current source supply for DMS [12-15] is shown in Figure 8 for SiO₂ at 60 kW. Full power is restored in the opposite polarity within about one half-cycle of shutting down to handle an arc. This likely represents the fastest possible response time for a pulsed dual magnetron reactive sputtering process, with less than a half cycle shutdown time; much less than the guideline of 1.0 msec or less suggested by the simulations.

**Figure 7.** Process response to 1.0 msec power supply shutdown in response to an arc.

**Figure 8.** Current fed DMS waveform showing improved arc handling with fast current reduction for a magnetron sputtering process operating at 60 kW.

**About the Author**

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David Christie received his PhD from Colorado State University, is currently Director, Applications Technology with Advanced Energy, and is serving his second term on the SVC Board of Directors. His first SVC paper was in 1996, on pulsed dual magnetron sputtering. He has more than 40 thin film related publications, and 6 related patents.

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