Power System Requirements for Enhanced Mid-Frequency Process Stability

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Key Words: Sputter deposition; Power supplies; Reactive deposition; Partial pressure control

ABSTRACT

Mid-frequency processes are commonly used for deposition of compounds by dual magnetron reactive sputtering. However, process stability has been an ongoing issue. Both plasma stability and reactive gas partial pressure stability need to be considered. Short-term process stability is strongly affected by the characteristics of the power system, including generator, cabling, and arc handling method.

Plasma characteristics for sputtering processes vary wildly with changes in gas pressure and content, exhibiting extreme hysteresis in some cases. The process power system must be carefully configured to provide short-term plasma stability.

In reactive sputtering processes, the flux of target atoms to chamber surfaces is shut off when the power supply output turns off for arc handling. This causes the partial pressure of the reactive gas to rise. It is necessary to respond quickly to an arc in order to maintain gas pressure within an acceptable range. We show how the partial pressure variation may be estimated with a simple dynamical process simulation model, and further develop arc detection and response time scale requirements for transition mode operation.

INTRODUCTION

Reactive sputtering is now commonly used to deposit compounds formed from sputtered target material and a reactive gas. These films offer many advantages but the process can be difficult to control, due to its highly nonlinear nature and essentially unmeasurable fundamental parameters, such as coverage fraction and ion flux. Figure 1 is a schematic depiction of a reactive sputtering process in which SiO_2 is formed. In the diagram, elemental Si from the target reacts with O_2 to form SiO_2 at the target surface. The O_2 is delivered by the natural flux to the target surface, determined by molecular flow gas kinetics which are governed by pressure, temperature, and mass of the molecules.

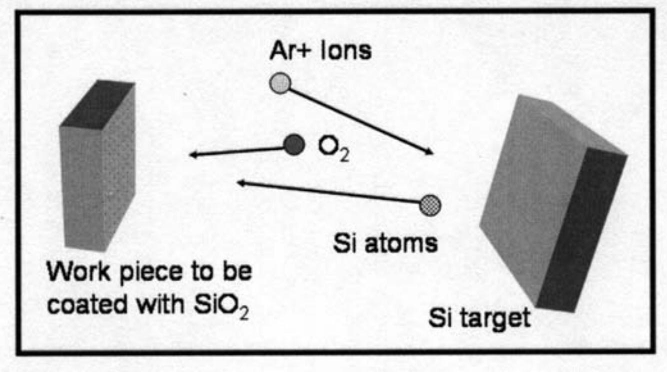

Figure 1: Schematic diagram of a reactive sputtering process.

Reactive sputtering has proven to be a useful technique for depositing a wide range of compounds. These include TiN, TiO_2, SiO_2, Si_3N_4, SnO_2, ZnO, and Al_2O_3, to name some of the compounds in common industrial use. Films of these compounds find applications in anti-reflective coatings, first surface mirrors, solar control coatings, automotive glass, architectural glass, hard coatings on tools and turbine engine blades, decorative coatings, and "lifetime" coatings on plumbing fixtures, just to name a few [1, 2]. Control of these processes has, however, proven difficult, due largely to extreme nonlinearities, driven by unmeasurable parameters. Control issues have motivated workers in the field to develop process models to aid in the understanding of the issues, with the hope that process control and performance would be enhanced. Of course, the desired outcome is broader application of these coatings, at lower and lower costs.

One consideration of paramount importance is the stability of the process. Stability can have broad meaning. There is, on one hand, the intrinsic stability that often implies freedom from oscillation, or perhaps, the ability to stay within a bounded 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 of insulating materials are by their nature prone to arcing. The dielectric material which forms on the target surface in some processes can accumulate electrical charge to the point where electrical breakdown occurs and an arc from the plasma to the target is initiated. When this occurs, the arc must be handled by the system's power supply. This typically entails an interruption in the power delivered to the process for a short 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 reapplied. When power is reapplied, the reactive gas pressure, target surface coverage, chamber surface coverage, electrical impedance, and deposition rate will have changed.

Variation of partial pressure as a function of arc response shutdown time has been previously investigated empirically [3]. However, 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.

A static model of the reactive sputtering process has been shown to capture the essential physics of the process at equilibrium. The Berg Model [4], although not the first to appear in the literature, is very straightforward and, perhaps, the most transparent. This model is based on equilibrium conditions (no dynamics) and simply tracks the reactive gas and the sputtered material to predict deposition rate and partial pressure of the reactive gas. The algorithm has been arranged so that it requires only one pass. That is to say, there is no recursion involved in the calculation of a particular point on the pressure versus flow and rate versus flow curves.

The flow of reactive gas is tracked from the gas inlet to three "consumers" in the process, as shown in Figure 2. The obvious destination for the gas is the system vacuum pump, but it is also getter-pumped at the target surface and at the chamber surfaces (including the workpiece). A simple continuity equation for gas flow is the result, whereby the input flow is equated to the sum of the flows to the target, chamber, and system pump. Total flow and flows to the pump, target, and chamber surfaces are assumed to be constant.

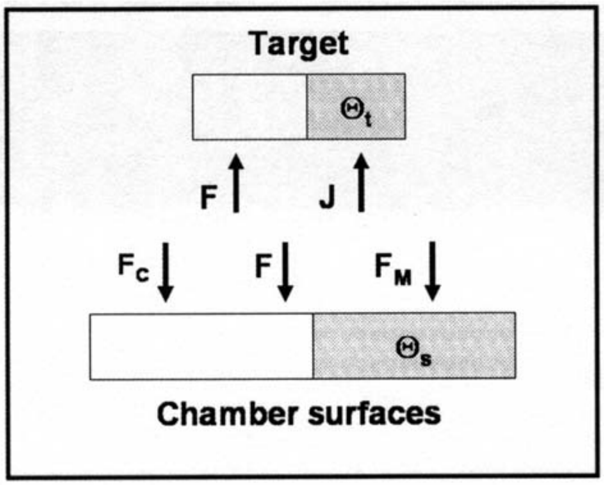

Figure 2: Reactive sputtering process model diagram.

The next part of the model tracks the fluxes of sputtered material to the chamber surface. Material sputtered from the target includes the compound formed at the surface by getter-pumping of the reactive gas as well as the intrinsic target material. It is assumed that the flux of material sputtered from the target surface is uniformly directed to the chamber surface, along with the flux of reactive gas. These fluxes are shown schematically in Figure 2, along with the ion flux directed to the target. Perhaps the key concept here is that both the target and the chamber surfaces have covered and uncovered fractions. In this context, the covered fraction is covered with the reactively formed compound. This is important for two reasons. The first is that getter-pumping occurs only at the uncovered surfaces, so covering a large fraction of the surface can significantly change the amount of getter-pumping that occurs. The second is that the reactively formed compound sputters with a significantly different yield than the target material in many cases.

MODELING

A dynamical model was created to examine the behavior of the process during an arc response. In particular, behavior of key internal parameters over a short time-scale is of interest. The model is the dynamical version of the Berg model, configured such that the internal states are partial pressure, target coverage fraction, and chamber surface coverage fraction [5, 6, 7]. This model was linearized at the approximate operating point in order to develop a control algorithm to stabilize it in the transition region [8] for the purpose of process simulation studies. The controller was designed using the linear quadratic regulator (LQR) technique [9] as a starting point for a manually tuned partial pressure feedback regulator. Simulations were performed with Simulink® [10].

Results of 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, 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 [11].

Table 1: Parameters used for large area TiO_2 process arc response simulation.

Parameter	Value	Comments
Target material	Ti	
Reactive gas	O_2	
Nominal compound	TiO_2	
Surface density of compound molecules	9.7E18 m^{-2}	
Ti sputtering yield	0.5	[11]
TiO_2 sputtering yield	0.017	[11]
Target area	0.264 m^2	
Chamber area	6.06 m^2	
Chamber volume	0.7 m^3	
Pumping speed	7000 l/s	
Temperature	300 K	
Sticking coefficients	1.0	[4]
Oxygen partial pressure	0.1 mTorr	
Oxygen flow	570 sccm	
Ar ion current density	1060 A/m^2	
Target coverage fraction	0.76	
Chamber coverage fraction	0.91	

The operating point for simulations in the transition region was chosen by using the static model, implemented in an Excel spreadsheet. Results are shown in Figure 3 and Figure 4. The transition region operating point chosen for the dynamical simulations is denoted by the black diamonds on the curves.

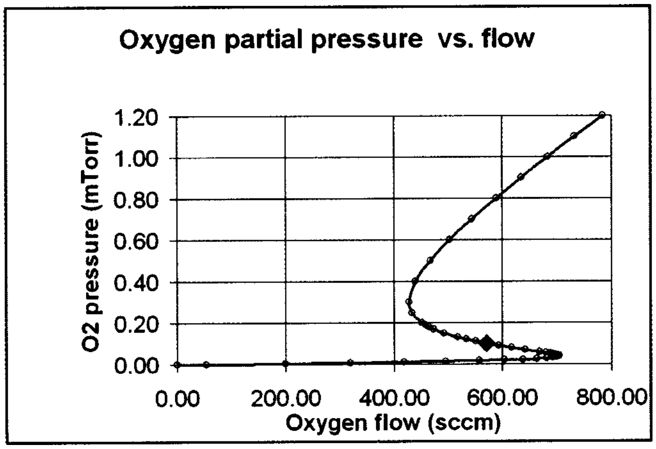

Figure 3: Oxygen partial pressure versus flow calculations from the static model. The operating point for the dynamical model is denoted by the large diamond on the transition region of the curve.

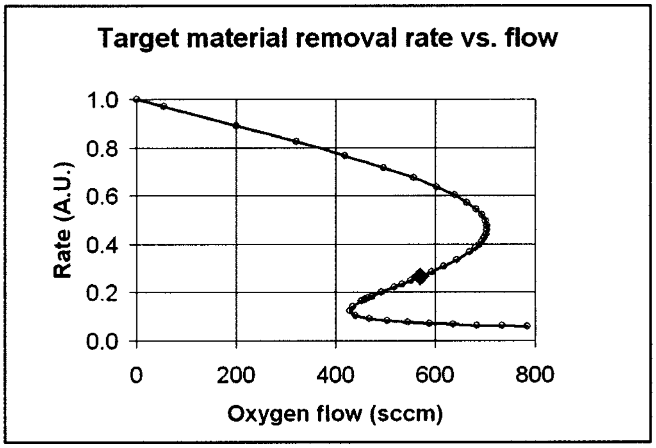

Figure 4: Deposition rate versus oxygen flow calculations from the static model. The operating point for the dynamical model is denoted by the large diamond on the transition region of the curve.

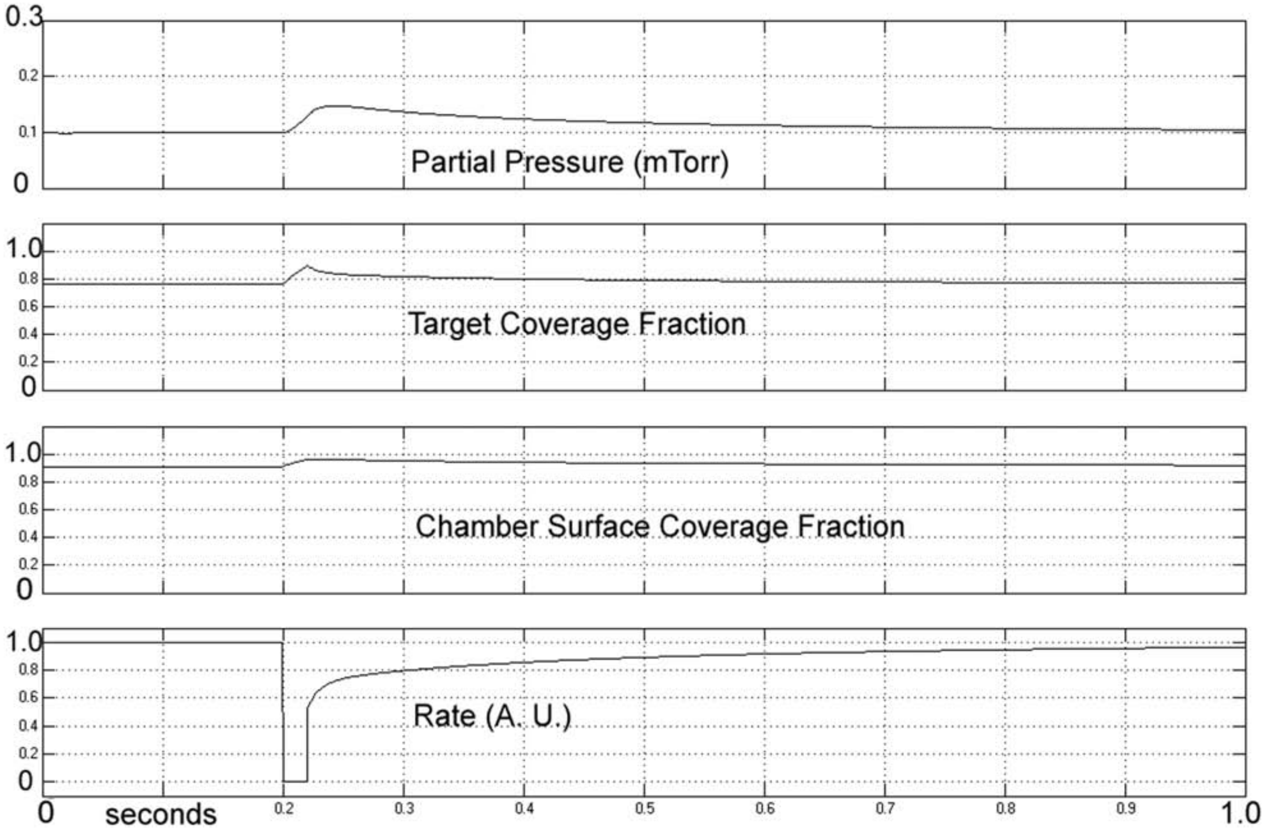

Figure 5: Process response to a 20-msec power supply shutdown in response to an arc.

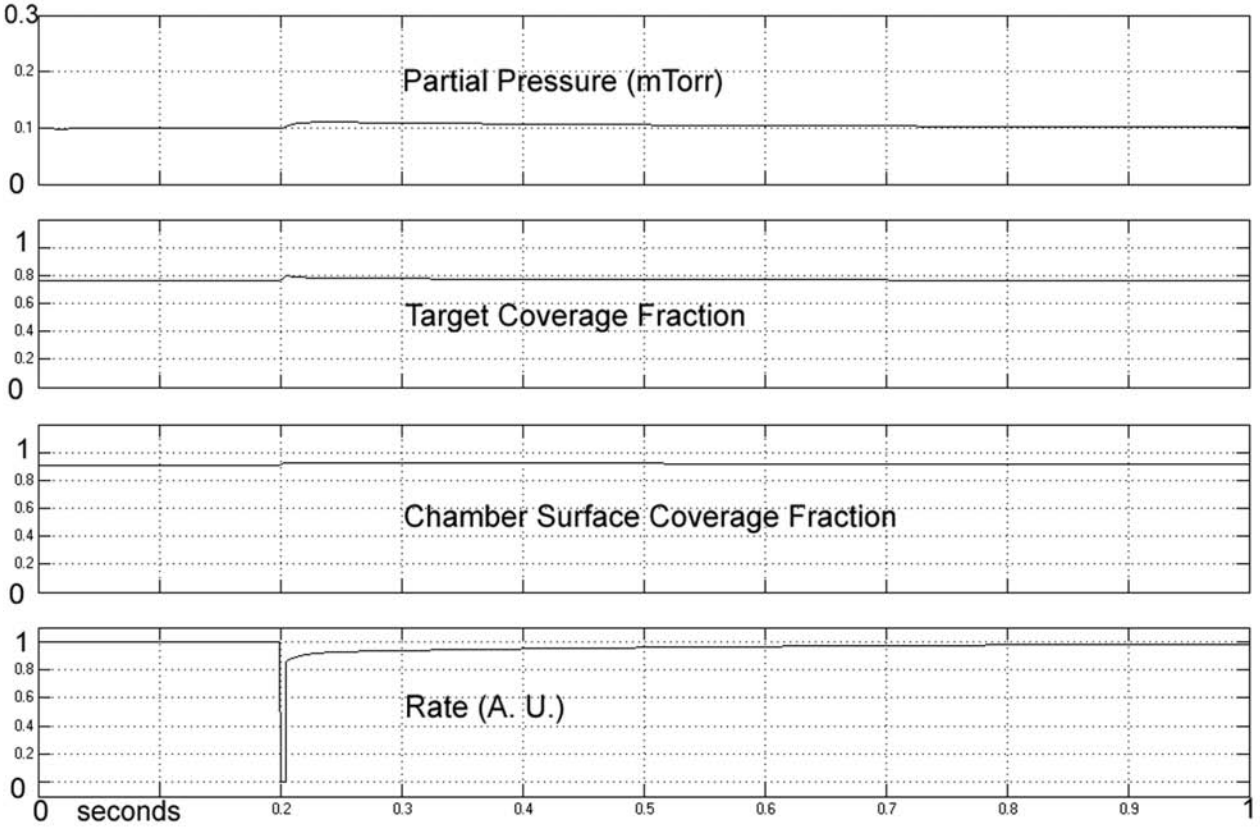

Figure 6: Process response to a 5-msec power supply shutdown in response to an arc.

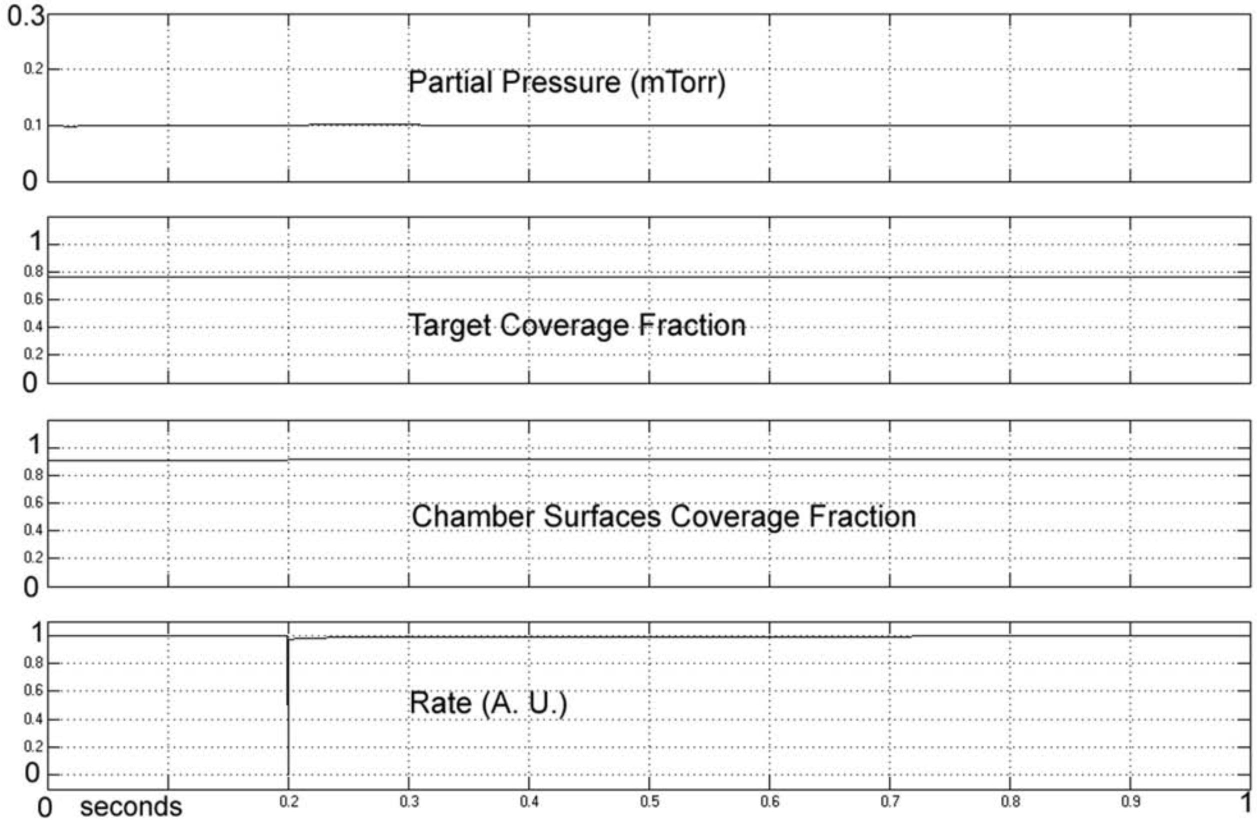

Figure 7: Process response to a 1-msec power supply shutdown in response to an arc.

Response of the process to a 20-msec arc shutdown is shown in Figure 5. The effect of the shutdown on the deposition rate lasts much longer than the shutdown time and would likely result in "banding" in an in-line glass coater. It seems unlikely that this process could be stabilized if shutdowns of this length occurred a few times a second.

Response of the process to a 5-msec arc shutdown is shown in Figure 6. Even a 5-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-msec arc response shutdown is shown in Figure 7. The longer term effect on rate is in the percent range. An arc response shutdown of order 1-msec or less allows process operation to continue seamlessly after power is restored.

ENHANCED STABILITY REQUIREMENTS

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. Resonant power supplies optimized for large area dual magnetron sputtering are capable of a complete arc response in less than 1 msec. Arc response from a resonant mid-frequency power supply optimized for plasma processing is shown in Figure 8 and Figure 9. Full power operation, at about 150 kW, is restored within 800 msec after the power supply shuts off to handle an arc.

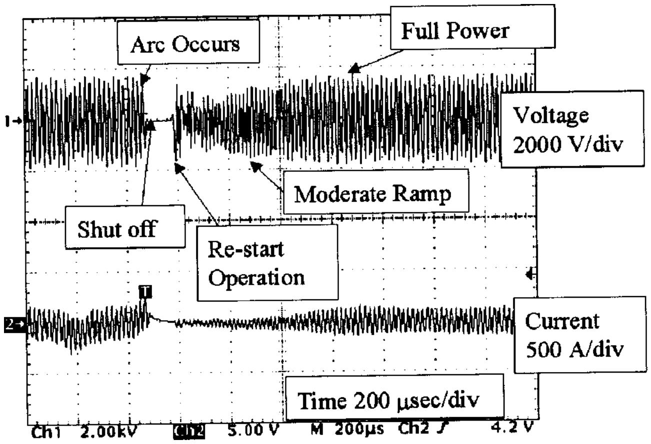

Figure 8: A 180-kW resonant power supply arc response, zoomed out. Full power is restored in 800 µsec.

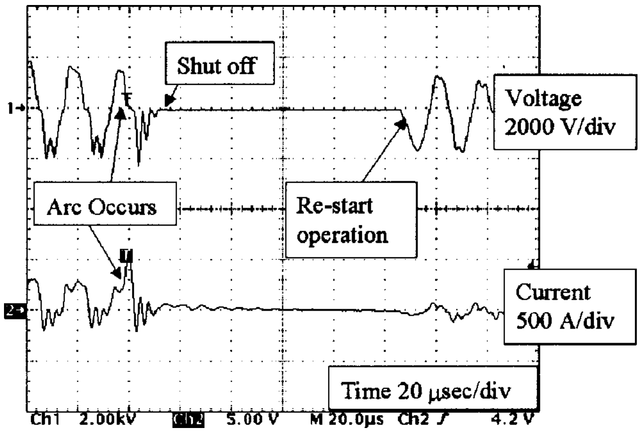

Figure 9: A 180-kW resonant power supply arc response, zoomed in.

An arc response from a mid-frequency dual-magnetron pulsed current source supply is shown in Figure 10. Full power is restored within one half-cycle of shutting down to handle an arc.

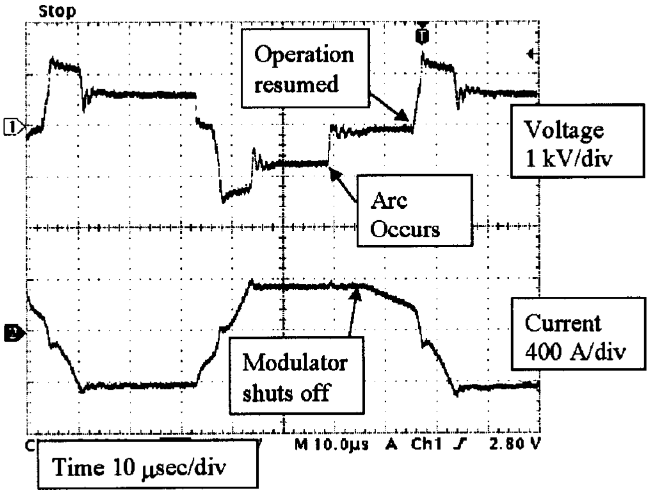

Figure 10: A 200-kW bi-polar pulsed power supply arc response.

CONCLUSIONS

Process simulations showed that power supply arc response shutdowns need to be of order 1-msec or less to minimize disturbance to a large area transition mode reactive sputtering process. Experimental data showed that resonant and pulsed current source supplies optimized for large area mid-frequency dual magnetron sputtering processes can have shutdown times of 800 µ sec or less.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to Bill Goldsworth for his assistance with the experimental arc response data.

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