Importance of Proper Deposition Rate Control and How To Achieve It

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ABSTRACT

In a typical optical coater, the goal is that, when the shutter opens, the material is depositing at the desired rate and that the rate does not vary until the shutter closes. This goal is not often well satisfied in the industry, and therefore can contribute to various problems in the optical and physical properties of the films. Guidance is provided in finding the various settings for a quartz crystal controller which will minimize these problems. Although some of this information may be familiar to many in the field, it is thought to be of enough potential benefit to others that it is reviewed here.

INTRODUCTION

The goal and the assumption is that, when the shutter opens to deposit a material on a substrate in a typical optical coater, the material is depositing onto the substrate at the desired rate and that the rate does not vary until the shutter closes. This goal is not often totally satisfied, and therefore can contribute to various problems in optical coating which will be addressed here. Figure 1 illustrates such an ideal case, where the shutter opens at time 0.1 and the rate is perfectly constant throughout the deposition.

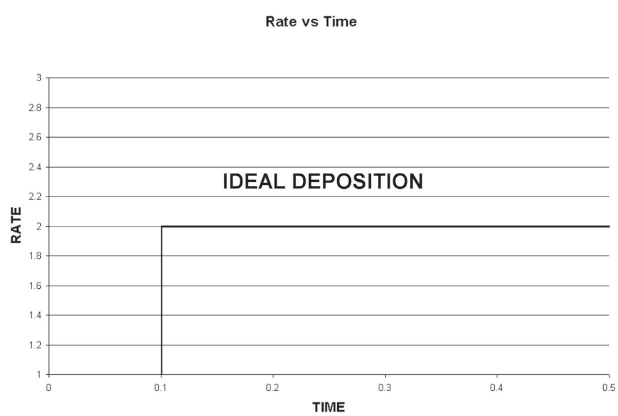

Figure 1: Ideal rate when shutter opens to exact desired rate and constant throughout.

THE PROBLEM

Perhaps the most serious problems arising from varying deposition rates occur with processes using reactive gases and ion assisted deposition (IAD). With a reactive gas process, higher than expected material deposition rates will allow for less reaction time and thereby possibly higher absorption, and the opposite with lower rates. It has been shown that the properties of the films deposited with IAD depend upon the atom-to-ion-arrival rate[1]. With a constant flux of arriving ions but a variable rate of arriving atoms (material), the properties of index (density), absorption, etc., can vary. Even with no reactive gas or ions supplied, the depositing material is competing for positions on the substrate with whatever the residual gas may be in the chamber (usually water vapor). For example, at 10^{-6} torr, one monolayer can form on the surface in one second to compete with the depositing film.

It may be possible that strong variations in the initial deposition rate when the shutter opens can also effect the adhesion of a film to the substrate from one deposition to another. It is also apparent that the homogeneity of the index throughout the film can vary if the rate fluctuates. These various effects can cause serious run-to-run differences which may be the causes of failure of some coating runs to meet specifications. The importance of these effects may be apparent to many in the industry, but there is also evidence that others have not been aware of how important they can be and how the problems can be reduced.

THE SOLUTION

Fortunately, quartz crystal monitors (QCM) are now installed on most optical coating systems, and they can control the deposition rates of most materials when used properly. The QCM normally generates a signal which is proportional to the amount of mass deposited on the sensor head. This information can be processed within the controller with the proper calibration factors to provide a rapid estimate of the deposition rate and thickness of the layer being deposited. This information can then be used to control the power to the deposition source for rate control and to open and close the shutter for

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that material. Gevelber, et al.[2-10] have extensively studied the application of the QCM to optical processes. However, one should be cautioned by the statement of D. Radgowski et al.[9] which said that “Benchmark studies of 30+ production systems revealed that none of the systems are reaching the full potential of their QCM’s rate control capabilities”.

There are three areas of QCM setup and operation that are important to this discussion. First is to get the proper constants set into the controller for each material, and the second is to get the power to the source such that the rate is very close to what is desired just as the shutter opens and the QCM starts controlling the rate. Third is to find what control delay is need for each material. There are various factors for each material to be entered from appropriate tables, but those which are addressed here are the PID control values. PID generally stands for proportional, integral, and derivative. One might chose to think in more descriptive terms of Push, Inertia, and Drag. Still other descriptions might be gain, momentum, and damping. One could imaging an example of pushing a stalled auto on a smooth and level paved road onto a soft sandy shoulder (all on the same level). As a push or force is applied, the sum of that force over time (integral) accelerates the mass or inertia of the auto up to some speed on the smooth pavement. As the sandy shoulder is reached, the friction or drag in the sand increases significantly over the drag of the road, and the auto slows or decelerates in proportion to the speed it was moving (derivative of distance versus time). The proportional aspect of the controller is that its correction signal or force applied is proportional to the error between the desired rate or set point (SP) and the rate at any given moment.

SETTING RAMP AND SOAK TIMES

To get some data on how the source behaves, manually bring up the power to the source with the shutter open until a small rate is detected. Control the source to keep a rate of 1 Å/second for about one minute, and record that power. Increase the power for a steady rate of 2 Å/second and record that power. Do this also by factors of two (4, 8, 16, etc.) until the maximum expected rate is covered.

It is next desired to get some data on the response time of the material system. With the shutter open, set the power for 1/2 the maximum expected for the deposition rate and wait until the rate is steady. Increase to power quickly to the power for the maximum expected rate and record the time it takes to reach 75% the desired rate, 85%, 95%, and 98%, as seen in Figure 2. Then turn the power down quickly to the value for 1/2 the rate and record the time it takes to reach a rate of 75%, 65%, 55%, and steady at about 50% of the maximum deposition rate.

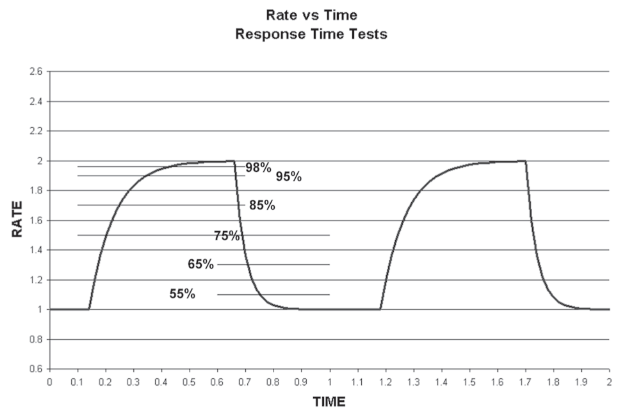

Figure 2: Testing the non-controlled response time for changes between 50% and full rate.

A possible starting setup for ramp and soak times would be as follows, but adjustments may be done as needed. As illustrated in Figure 3, set the RAMP 1 Time to the time found above to reach about 95% rate, and set the RAMP 1 Power to the level found which just starts to evaporate material at a very low rate. Set the SOAK 1 time the same as the RAMP 1 Time and the SOAK 2 Power to the same as the RAMP 2 Power. Then set the RAMP 2 Time the same as the RAMP 1 Time. Set the RAMP 2 Power to the power determined above for the desired rate. Set the SOAK 2 Time and SOAK 2 Power to the same as RAMP 2 Time and Power.

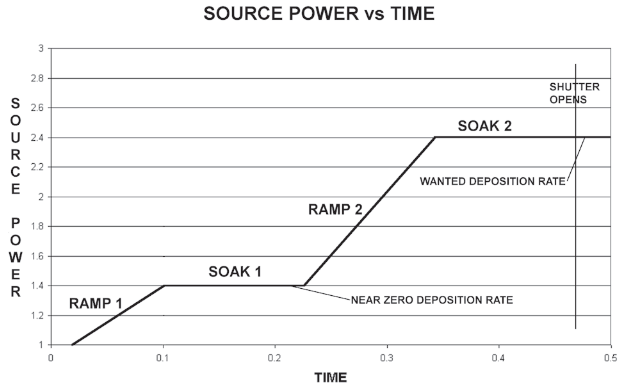

Figure 3: A possible ramp and soak power and time plan.

The HOLD Power is for use when another material is being evaporated and the one considered here is waiting to be used for another layer. This should be set to the same level as SOAK 1 power. This then should evaporate very little material while on hold, but be ready to ramp up to deposition rate when needed by the application of RAMP 2 and SOAK 2.

PID TUNING

Figure 4 illustrates a set point (SP) of 2 units of rate (perhaps in Å/second) and an initial rate of 1 unit when the shutter opens at time equal zero. The QCM controller then needs to Push (P) the power to the source until the rate is 2. The figure shows that a P-value of 0.2 will cause the rate to come close to 2.0 in about 0.5 time units (perhaps minutes). As the P is increased to 0.4, 0.6, 0.8, and 0.95, the rate more and more quickly reaches the SP. This would be the same as getting the auto in the example above to where it is wanted more quickly by pushing harder on it to speed up the process.

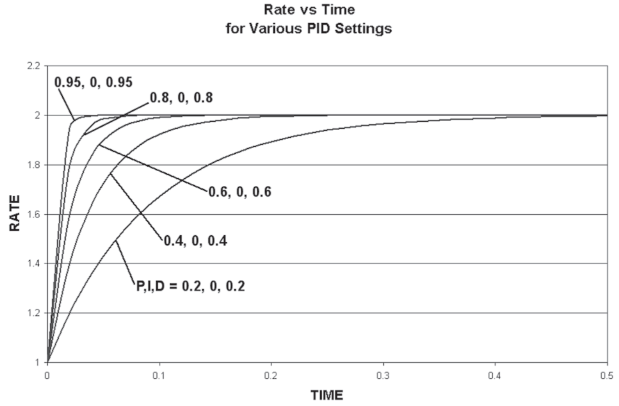

Figure 4: Various PID settings with critical damping showing relative response times.

The curves in Figure 4 are all for D-values of the "PID" which provide "critical damping". This means that the rate gets to the SP as quickly as possible for that amount of gain (P) without going beyond the SP or overshooting. Figure 5 shows that the P of 0.95 in this case with no damping (D = 0.0) would cause major overshoot to occur and oscillations. The rate is varying here from 1 to 3 and back with gradually decreasing amplitude. This is far from the desired behavior. Figure 5 shows the effects of increasing amounts of damping of 0.4, 0.8, and 0.95 until critical damping is reached and the rate quickly comes to the SP without an overshoot. The goal is to have the rate reach the SP as quickly as possible and to stay there.

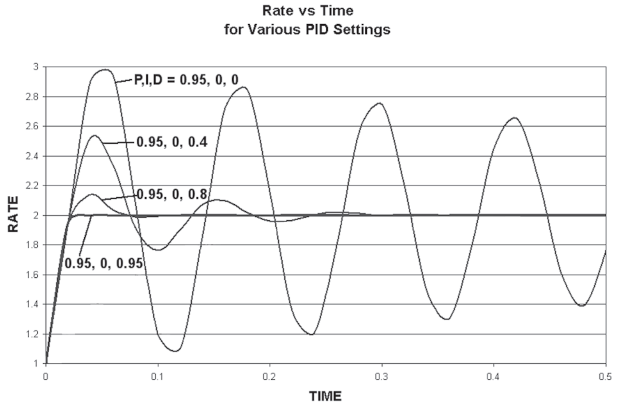

Figure 5: Various damping (D) values from zero to critical damping for a gain of P = 0.95.

One would therefore like to have as high a gain (P) as practical which is to be critically damped by the D-value. This will correct any rate error as soon as possible without an overshoot. Too much damping can, however, delay reaching the SP. A small overshoot may be practical to show that the system is not overdamped.

The I-value may not need to be used, depending on the system. In that case, the tuning procedure or selection of the P- and D-values can be fairly straightforward.

It is recommended that the following procedure be used on tuning resistance sources initially, since e-gun depositions add new factors to be handled. Set up the QCM as needed and manually control the power to start depositing at 1/2 the desired rate until steady. Start the QCM automatically controlling at that rate for perhaps 1/2 minute. This should be steady. Change the SP to the full desired rate and record pattern of rate versus time as in Figures 4 and 5.

If the pattern shows oscillations as at the start in Figure 6, increase the D-value by a factor of two. Then cut the rate SP to 1/2 of the desired SP; this will create another transition/change in the other direction which can be observed for oscillation as in Figure 6. If there are still oscillations, increase the D-values again by a factor of two, and set the SP back to the desired (higher) rate. Continue this procedure until the transition is nearly critically damped, as at the right end of Figure 6.

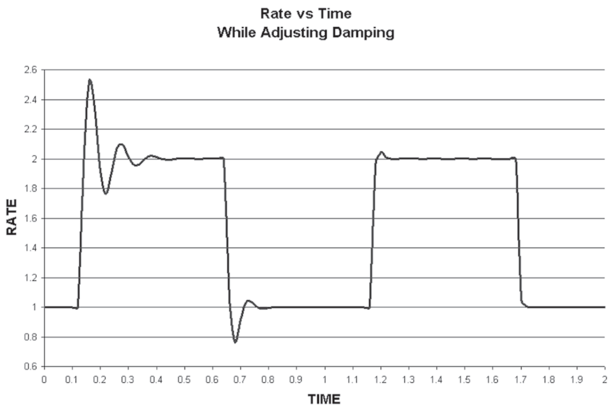

Figure 6: Adjusting damping to higher values to reduce overshoot and "ringing."

If the initial pattern shows no oscillations as in Figure 7 (rather than that of Figure 6), increase the P-value by a factor of two and cut the rate SP to 1/2. This will create another transition/change in the other direction which can be observed for oscillation. If there are still no oscillations, increase the P-value again by a factor of two, and set the SP back to the desired rate. Continue this procedure until the transition has shown some oscillation but is nearly critically damped as at the end of Figure 7.

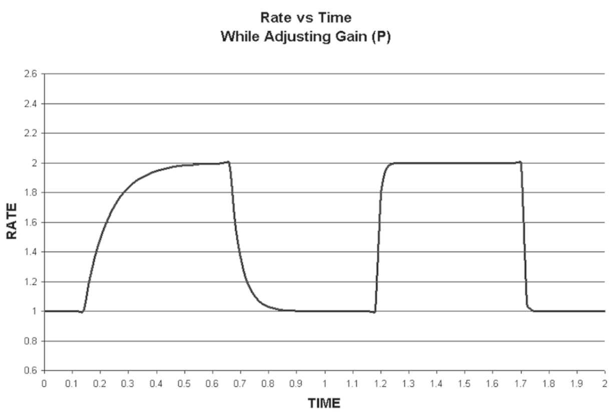

Figure 7: Adjusting gain (P) to higher values for faster response.

The above procedure should provide good constant rate for an otherwise stable source. However, it may be possible to obtain an even faster response. This should be explored by increasing to P-value and D-value in steps to keep near critically damped at higher and higher values of P. These would be expected to reach some practical limit which would not be beneficial to exceed. At that point, it is advisable to back down a small amount for a margin and use that as the operating PID values for that particular material source.

These results may have some sensitivity to the size of the load of material in the source. That might require some further tests with a near-full and near-empty source.

SOAK LEVEL BEFORE SHUTTER OPENS

It is intended to have the source soaking at a power such that the deposition rate will be exactly that desired when the shutter opens. Set the crystal controller to display the rate but to NOT control the rate. Set the SOAK 2 power to give the SP rate. When the warm-up cycle is complete, open the shutter and record the behavior with the power constant to determine when the steady rate is reached after the shutter opens. There may be some transient effects as seen in Figure 8 for a short time and then a constant rate because the power is constant. If the final rate is to high or low, adjust the SOAK 2 power until the rate is correct. Record the time of the transient behavior with each such test.

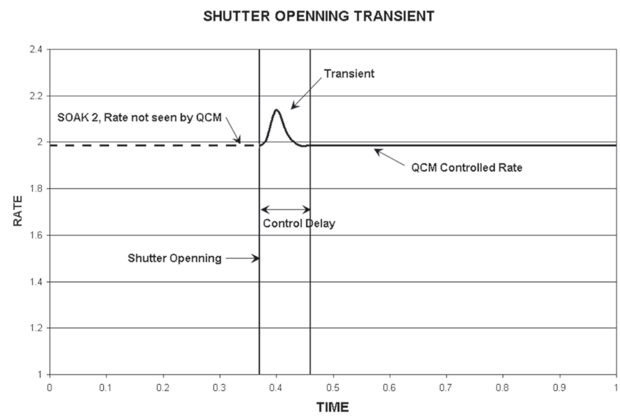

Figure 8: Control Delay needed to ignore effect of transient when shutter opens.

CONTROL DELAY AFTER SHUTTER OPENS

The above tests will determine the value needed for the Control Delay in the Crystal controller. Enter this value in the controller settings for this material. The need for this usually arises from the effect of radiant energy reaching the crystal sensor from the source when the shutter opens. It causes a rise in temperature of the crystal which gives a false indication (higher or lower) of the rate until the transient passes. The Control Delay prevents the controller from acting until it has information which is thought to be correct. Otherwise, the transient is likely to further aggravate and defeat the purpose of having a perfectly constant rate while the shutter is open.

CONCLUSIONS

Constant deposition rates during deposition of thin films are important to the reproducibility of the index values and other physical properties, but this goal may not be often achieved.

The behavior of the control functions of a quartz crystal monitor are described. Procedures are suggested to optimize the related control values.

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