Choosing A Chamber

By

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Abstract:

In the last 15-20 years the equipment used to deposit optical thin film coatings has changed dramatically. In years past, a typical coating machine was completely manual or semi-automatic at best and required a highly skilled operator to produce consistent results.

Today, a top quality optical coating machine blends an eclectic collection of smart subsystems into a fully automated deposition system. These subsystems are usually supervised by a number of microprocessors, which are then integrated into a local area network (LAN), which in turn is tied to an overall factory automation system. The increasing sophistication of the user translates to ever more demanding specifications for system performance; it is not unusual for customers to buy process expertise along with the machine. In this article we examine the components and subsystems which are available for today's optical coating systems, and we look at how process issues tend to dictate component selection and chamber configuration. Although other technologies are becoming popular, we will focus on physical evaporation as it is still the most widely used and versatile of the available technologies.

I. Introduction

The production of thin film dielectric coatings for precision optics and ophthalmic applications has long been dominated by evaporative techniques. Resistance and electron beam deposition sources, alone or in tandem with energetic ion sources – both to facilitate substrate pre-cleaning and to modify the properties of a growing film - have been implemented in thousands of systems worldwide. Dielectric coatings produced by magnetron sputtering have been very successful in niche applications, restricted to narrow, high volume applications such as architectural glass. The system costs tend to be high and the performance targets relatively simple (stress management in sputtered thin films is the process limiting parameter). Secondary ion beam sputtering has been employed in very narrow applications like ring laser gyros and wavelength division multiplexing (WDM) filters, where the extremely low deposition rate can be considered a manufacturing process advantage.

All in all, the long throw distances required for evaporation have been indirectly very useful at producing uniform coatings over the curved surfaces found on the bulk of the optics required by the photonics industry. Coupled with high deposition efficiencies, modern controls and automation (particularly quartz-crystal rate controllers and in-situ optical monitoring), evaporative systems offer a robust production solution to many optical thin film requirements.

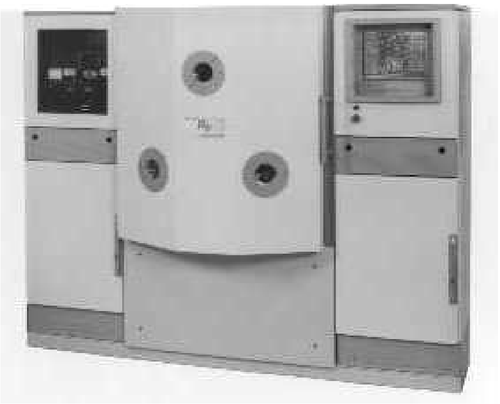


Figure 1: A modern turn-key system requires no intervention by an operator

The components and subsystems required to manufacture a modern evaporative coating system are available in a limited size and performance range. Automation, instrumentation and controls can be considered fixed costs for they do not vary substantively with system size, and they generally account for a significant portion of the total system costs. These two phenomena result in a cost vs. capacity inversion. In general, a modern evaporative system's capacity scales geometrically with the acquisition cost.

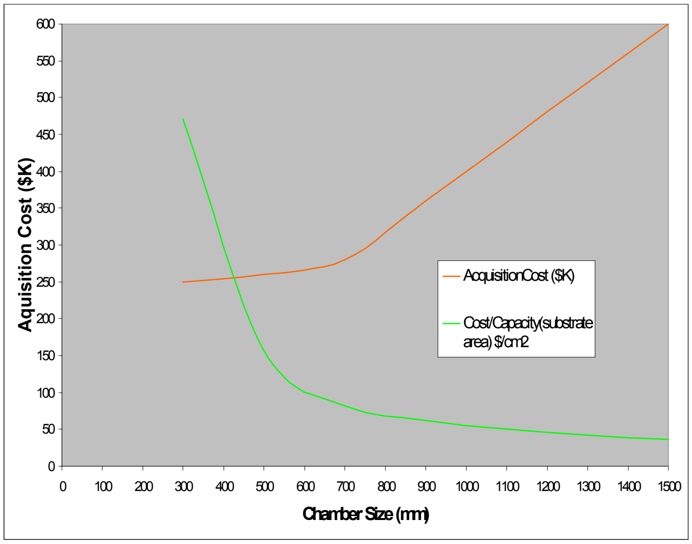


Figure 2: Cost per Capacity is much higher for smaller systems

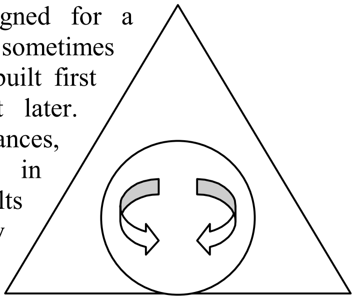
Although this argument delights the modern deposition system manufacturer, the converse has significant economic implications. As price is reduced, the capacity roll off is so severe that a discernable lower limit in system size is reached. (Figure 1) Currently, this value is approximately $250K (US Dollars) for a modern evaporator with an internal volume exceeding 175L, generous pumping speed (> 1500 l/sec air speed) and capable of executing ion beam assisted deposition (IBAD). There do not appear to be any significant technical breakthroughs on the horizon that might significantly lower this cost.

The pressure on deposition system manufacturers to deliver high performance optical coatings from small, simple systems has increased over the past few years. In addition, the performance bar has been raised, particularly in terms of film density and its' role towards minimizing spectral shifts due to water uptake. Average lot sizes have gone down and the production of optical coatings is now being transitioned into technically unsophisticated environments.

As a consequence, the specification and selection of a modern optical coating system must be driven by careful consideration of the performance targets of the desired coating design, the substrate's size and physical characteristics, and the technical elements necessary to guarantee a high level of process repeatability.

II. Optical Performance – The Tolerance Triangle

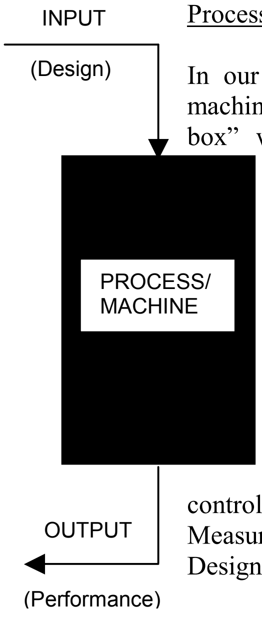
To develop a thin film coating system that will yield consistent product, the components of the system – the Design, the Process & Machine, the Performance Objective – must be properly matched and take into account the expected manufacturing tolerances; the machine must be designed to fit the process, rather than the process adapted to fit a machine. This is not true of many optical coating systems currently in use; in some instances processes are running in equipment which was originally designed for a different application. Or, as sometimes happens, the machine was built first and an application sought later. Whatever the circumstances, when a system evolves in reverse, so to speak, the results are unlikely to be satisfactory because the machine may not be adequate to produce the desired performance.



There are three aspects to consider when selecting and specifying a thin film coating chamber. They are all linked through the manufacturing tolerance of the system:

Input-Design

This is the "recipe" – a coating design defines the layer structure, thicknesses and refractive indices which, if properly reproduced by the Process/Machine, will result in measured output which meets the Performance Objective.



Process&Machine

In our extended definition, the process and machine can be regarded together as a “black box” which accepts the Design Input and produces the Measured Output. In reality, the process will consist of machine hardware, control software and a set of instructions that allow the machine to implement the Design. Within this Process/Machine there are many variables, some of which are imperfectly controlled. These variables give rise to the manufacturing tolerances of the system which limit the ability to control layers thicknesses and cause the Measured Output to be different from the Design.

Output - Measured Performance

Ultimately this is what really matters. For the process to be viable, the Measured Output must meet the Performance Objective – usually a customer specification for optical performance and durability – the majority of the time.

It is important to understand that these three elements are dependent on one another and so cannot be considered in isolation. In a well-matched system, the Design and Process/Machine will be such that the Performance Objective will always be met, despite manufacturing tolerances. However, if any of the three is changed, the others must be reconsidered to ensure that the system has not become mismatched. For example, if a good process is scaled up, the larger machine may have greater manufacturing tolerances that require that the Design be improved or the Performance Objective be reduced. Or, the customer may increase his Performance Objective in a way that can apparently be satisfied by a simple change in the Design. However, if the new design is more sensitive to thickness variations, it may not be possible to meet the new performance objective consistently without also modifying the process to reduce manufacturing tolerances.

Some aspects that must be considered when evaluating the tolerance of a process:

Thickness Monitoring: The thickness accuracy of each layer in the design is limited by the accuracy of the device used to control it, usually either a Quartz Crystal Microbalance (QCM) or an Optical Monitor, or both. For the QCM, accuracy is about 2%, while for a well designed optical set up it can be a fraction of a percent.

Thickness Non-Uniformity: No matter how accurate the monitor, it can only control the film thickness at a single location inside the chamber – usually in the middle of the substrate rack. If the thickness is not perfectly uniform across the rack, substrates that are positioned away from the center will not receive the same thickness. Masking can eliminate non-uniformity that exhibits a consistent pattern, but some thickness variations are caused by erratic sources or by differences in material behavior, and are therefore almost impossible to eliminate. Appropriate selection of chamber geometries and evaporation sources can minimize these effects.

Time Variation: It is common for the deposition conditions in the chamber to vary over time. Within a run, the source characteristic will change as the material becomes depleted, particularly if the design involves many thick layers, and thermal gradients inside the chamber are likely to evolve if the process lasts several hours. Also, from run to run there tends to be a gradual shift in performance as coating deposits build up on the walls and the chamber becomes “dirty”. To the extent that these factors are progressive, they can be compensated for, but they must be considered as part of the overall tolerance of the system.

Moisture Shift: Thin films tend to be porous, giving them properties that are inferior to bulk material in many ways. One consequence is that the voids in the microstructure can fill with water vapor under humid conditions, and “dry out” when relative humidity is low. The presence or absence of water in the films changes their effective refractive indices, causing the well known phenomenon of *moisture shift*, a change in the spectral characteristics of the coating. The deposition conditions exert a powerful influence on the porosity of deposited films: it has been well established that high substrate temperatures

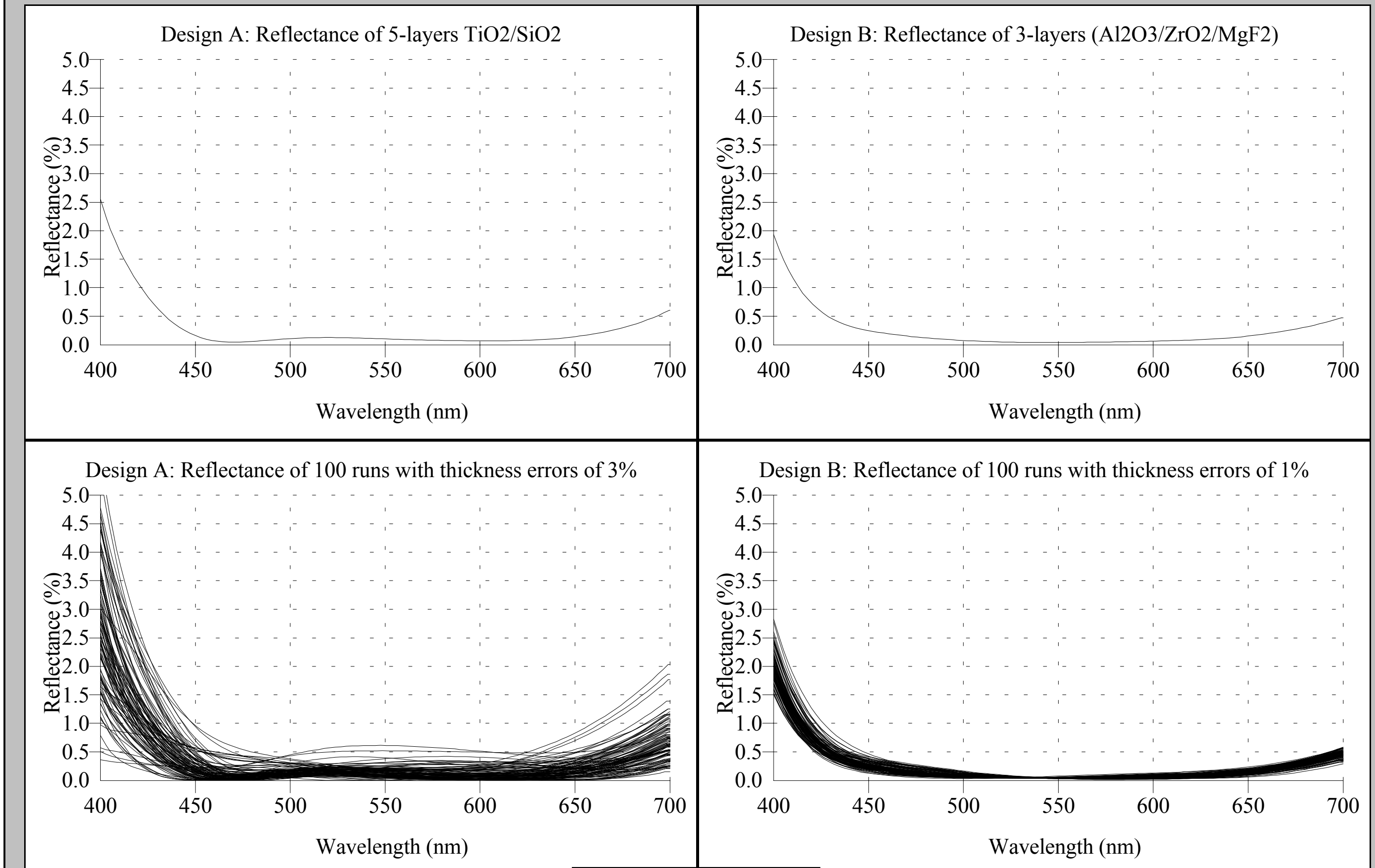
(~300°C) can increase film density, and, more recently, Ion Beam Assisted Deposition (IBAD) has been used to virtually eliminate moisture shift, even at ambient temperatures.

It is obvious, then, that the Machine/Process element must be considered at a level beyond basic component function. The selection of each item must only be made after a careful assessment of its impact on manufacturing errors and control of the process.

III. System considerations:
The issues that must be addressed when designing a modern deposition system to match specific performance criteria are so many and so complex that the task can seem overwhelming. To start it is usually best to consider the required performance of the coatings, together with the nature of the substrates to be coated, and work from there towards selecting a system that will function well. Firstly, the coating design will include expected film properties, both optical and

The Errors of Our Ways

A simple example of how important it is to consider tolerances can be seen in Figure 3. Two anti-reflection (AR) designs are shown. Both easily satisfy a requirement for 0.3%R between 450-650nm, but it would seem that Design A (5-layers, TiO_2/SiO_2) is better, being a little broader and flatter than Design B (3-layers, $Al_2O_3/ZrO_2/MgF_2$). However, we know from experience that we must expect larger thickness errors for an SiO_2 based coating because an SiO_2 source tends to be much less consistent in its behavior than an MgF_2 source. In a large chamber, SiO_2 layers might be subject to 3% errors, whereas MgF_2 layers can be controlled to within 1%. When such thickness errors are introduced to the AR designs, we see that in fact Design B will produce much better results than Design A.


Design A: Reflectance of 5-layers TiO2/SiO2

Design B: Reflectance of 3-layers (Al2O3/ZrO2/MgF2)

Design A: Reflectance of 100 runs with thickness errors of 3%

Design B: Reflectance of 100 runs with thickness errors of 1%

Figure 3

mechanical, which will lead to selection of materials and in turn to source types and deposition conditions. Secondly, the degree control (of optical thickness) necessary for the design to produce consistent results tends to dictate the selection of thickness monitor, substrate rotation and source layout. The substrate itself can exert a powerful influence on the selection process in that some materials can not be heated, and the size and shape of the parts will often dictate the type of rotation system and uniformity masking.

Pumping:

The components of the pumping stack must be carefully selected to allow the desired level of vacuum to be achieved in the required time. Effective pumping speeds can be calculated from the pump specifications and chamber conductances, but since the major gas load is almost always water vapor, pump down times are limited by the water vapor pumping speed of the system. When large water loads are anticipated, auxiliary cryogenics are often added in the form of Meissner panels to increase water vapor pumping speed. Cryopumps are clean, effective, fast and oil free, and have become the high vacuum pump of choice for small and mid-sized systems. On larger chambers, which tend to have greater thermal loads, both from process gases and radiated heat, cryopumps can encounter refrigeration difficulties. The classic combination of diffusion pump and cryogenically cooled baffle remains the most flexible pumping stack and it comes into its own on larger systems, particularly when hot processes are involved. The roughing pumps must also be given some consideration beyond simple pumping speed. For a diffusion pumped stack, a blower package is desirable to cross the gap that exists between the effective operating ranges of the diffusion pump and the mechanical pump. A cryopump can tolerate a higher crossover pressure, and so a mechanical pump will suffice, but it should be 2-stage for applications where large water loads are expected.

Evaporation Sources:

The simplest way to evaporate material is by resistance heating of a coiled basket or boat. These low voltage sources are simple, inexpensive and reliable, coming in a wide variety of sizes and shapes, with correspondingly different electrical characteristics; a small coil used to deposit a thin metallic film might only require 50A, whereas for Infrared filters, where the layers are much thicker than for visible coatings, high capacity boats are required which can draw up to 1000A.

Many materials cannot be evaporated thermally, including most of the dielectrics that are commonly used for visible and near infrared (NIR) coatings, and for those an electron beam gun must be used. A large variety of sizes and types is available; multi-pocket guns allow several materials to be evaporated from one source and work well for multi-layer coatings with a small number of thin layers. When complex designs require a large quantity of each material, or if it is necessary for each source to occupy a different location, then high capacity single pocket guns are used. Power levels are governed more by the thermal conductivity of the material than by its' evaporation temperature. Power supplies range in size from 4kW, which is quite adequate for most dielectrics, to 10kW or more, which might be necessary for very high rate deposition, or for thermally conductive materials in a large chamber.

A good beam sweep controller is essential for consistent evaporation of dielectrics by e-gun. Traditionally they have taken the form of analog waveforms which drive the beam electro-magnetics, both laterally and longitudinally, and have adjustable amplitude and frequency. More recently, versions have become available that divide the crucible into pixels and allow variable dwell time at each point. In either case, to be integrated into an automated system, the sweep controller must include a number of preset patterns which can be selected by the control program.

Process Conditions:

The expected deposition conditions will obviously play a role in the selection of much of the chamber equipment; heaters, ion source, glow discharge, pressure & gas flow instrumentation, residual gas analyzer (RGA) and even the pumping system itself are all affected by such aspects as the process temperature, the addition of reactive gases, and the use of ion beam assisted deposition (IBAD). High substrate temperatures offer many advantages in terms of film properties, but make the process more complicated and time consuming, and are simply incompatible with some substrate materials, such as plastics. DC glow discharge and an ion source have overlapping functions; for simple substrate pre-cleaning the glow discharge suffices; if an ion source is to be used for IBAD then it can also serve, very effectively, for pre-cleaning and the glow becomes redundant. Glow discharges operate in the 10^{-2} torr range and so call for large gas flow controllers and a low conductance high vacuum bypass valve to shield the high vacuum pump from high inlet pressures. Conversely, ion sources typically operate at much lower gas flows and pressures; high pumping speeds are desirable to maintain the lowest possible pressures during IBAD layers. Some processes are contamination sensitive; a residual gas analyzer (RGA) is an extremely valuable tool as it can reveal the presence of abnormal gases or vapors at orders of magnitude lower than the total chamber pressure.

Substrates & Fixtures:

Size, number, daily throughput, allowable jig marks, coefficient of thermal expansion, fixturing, thermal shock resistance, outgassing characteristics, thickness uniformity and special handling requirements are all important considerations in deciding how to hold and rotate the parts inside the chamber. If the process is hot, careful attention must be paid to thermal expansion and dimensional tolerances – of both the fixture and the substrate - to avoid the possibility of the substrates' being dropped or crushed during the temperature cycle.

For thickness uniformity, a double rotation, or planetary motion, gives the best results, especially on substrates with some curvature. In fact, for steeply curved parts, it is the only way to minimize thickness variations across each part and from part to part within a run. Unfortunately, planetary systems do not allow efficient loading of the chamber; capacity, and therefore productivity, tend to be compromised in this quality-based approach.

If the desired level of uniformity can be achieved with single rotation then an arrangement with a domed calotte offers much more efficient use of chamber space. In either case, a uniformity mask of some sort will be required to correct whatever thickness variations are inherent in the geometry. Theoretical calculations can provide a good starting point for these masks, but their ultimate shapes are determined empirically.

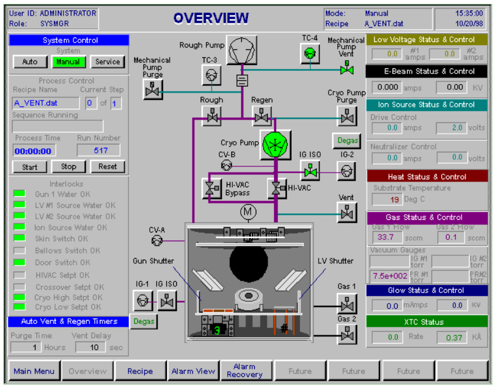
Thickness Monitoring & Control

The most straightforward method for deposition control is a Quartz Crystal Microbalance (QCM). Such instruments can drive the sources directly, handle ramp and soak stages, actuate the shutters and maintain rate via PID control loop. The entire deposition can be controlled by a single instrument which interfaces easily with the system control software. Dual, shuttered sensor heads are available to provide a safety backup, or allow for thick multi-layer deposits. However, the accuracy of a QCM is limited, in part because it controls the *mass* of the deposited film rather than its *optical thickness.* Furthermore, while the QCM is very stable at low process temperatures, the crystal response becomes highly temperature sensitive at higher temperatures. During long hot processes it is very difficult to prevent the sensor from drifting into this sensitive range and resulting in significant layer termination errors.

Optical monitoring is the preferred technique for high precision coatings since (when done correctly) it gives higher accuracy and precision in controlling layer thicknesses. The improved accuracy arises from a number of advantageous factors, the most fundamental of which is that *optical thicknesses* are being monitored. This can be directly on the substrate, if direct monitoring is employed, or on a separate monitor chip, as in the case of indirect monitoring which is more flexible but allows the possibility of a discrepancy between the chip and the substrate. A number of refined strategies have been developed over the years to enhance the sensitivity of the optical response to thickness changes and so reduce termination errors. Optical monitoring software typically will contain provisions for choosing reflection or transmission modes, and selecting a wide range of monitoring wavelengths. Wavelength selection may be done using narrow band filters or monochromators. The latter technique is more expensive but gives continuously selectable wavelengths over a wide range. Additional wavelength selection is available using monochromators with multiple gratings. Ultra violet, visible and infrared regions each present unique problems: light sources and detectors must also be chosen carefully to match the operating wavelengths of the monitor.

System:

Most of the internal chamber equipment will be based on the preceding discussion. As for chamber dimensions, most manufacturers offer a comprehensive range of standard sizes, but there may be special applications that call for unusual layouts. It is important to consider how the operator will have access to the components that need regular attention, such as the sources, monitor chips and, of course, the substrate holders. Electrical services, cooling water requirements, special utility considerations, work flow management and specialized ancillary equipment should all be considered at the system design stage. In terms of system control, at a minimum there will be local program application for Supervisory Control And Data Acquisition (SCADA). At the customer site there may be other interfacing issues such as connecting to the local area network (LAN). In the highest level arrangement there will be an internet link to the equipment manufacturer who can then monitor system performance and offer process diagnostics from a remote location.



User ID: ADMINISTRATOR
Role: SYSMGR
Mode: Manual
Recipe A_VENT.dat
15:35:00
10/20/98
Recipe Name: A_VENT.dat
Current Step: 0 of 1
Process Time: 00:00:00
Run Number: 517
Interlocks
🟩 Gun 1 Water OK
🟩 LV #1 Source Water OK
🟩 LV #2 Source Water OK
🟩 Ion Source Water OK
🟩 Skin Switch OK
☐ Bellows Switch OK
🟩 Door Switch OK
☐ HIVAC Setpt OK
☐ Crossover Setpt OK
🟩 Cryo High Setpt OK
🟩 Cryo Low Setpt OK
Purge Time: 1 Hours
Vent Delay: 10 sec
Low Voltage Status & Control: 0.0 #1 amps; 0.0 #2 amps
E-Beam Status & Control: 0.000 amps; 0.00 KV
Drive Control: 0.0 amps; 2.0 volts
Neutralizer Control: 0.0 amps; 0.0 volts
Substrate Temperature: 19 Deg C
Gas 1 Flow: 33.7 sccm
Gas 2 Flow: 0.1 sccm
Vacuum Gauges: PR #1 7.5e+002 torr
Glow Status & Control: 0.0 mAmps; 0.0 KV
XTC Status: 0.0 Rate; 0.37 KÅ

Figure 4: It is common for full system control to be available through a Windows® based graphical interface

IV. Applications:

The applications for optical coating systems are so many and varied that it is impossible to cover them all in one article. We have chosen two of the most popular: an Ophthalmic machine geared towards high volume production of AR coatings on eyewear, and a Precision Optics machine which is more versatile, capable of more complex coatings and higher precision.

Figure 5: Domed calotte, electron beam gun and ion source are visible in this ophthalmic coater.

Ophthalmics (eyeglasses and sunwear; predominately plastic substrates): – Most designs feature SiO_2 and TiO_2 and so an electron beam gun is used as the primary deposition source; operating power levels of 4-6 kW are required at most. Resistance evaporation may be used to deposit a thin, adhesion promoting underlayer (Cr.) or a hydrophobic overcoat (high vapor pressure polymer); these sources are typically quite small with low power requirements (2 kW). Heaters are typically included but since they are used for initial ballast heat and to promote outgassing, they also are quite small in wattage (1-3 kW). Ion sources - cold cathode or end-hall - are essential to promote adhesion through a low energy bombardment and surface modification prior to the deposition sequence.

High water pumping speeds are critical to handle the copious amount of water vapor evolved from the substrates, therefore these systems generally have auxiliary cryogenic pumping. Sizes traditionally range from 700 mm to 1250 mm; the larger systems usually being diffusion pumped. The smaller systems are most often cryogenically or turbo pumped. Fixturing is generally a single rotation domed calotte to maximize capacity when coating stock lenses and flip-over is universally employed when coating edged prescription lenses. Wrap around goggles (sunwear and safety glasses) require special masking for uniformity of color. Thickness control of about 2% is considered adequate for this application; deposition rate and end-point determination are handled by a QCM controller.

<u>Precision Optics</u> – Coatings for the precision optics market segment can be categorized by a broader range of products and process requirements. At the low end of the complexity curve, coating designs similar to ophthalmic applications may be executed. On the high end, coating designs consisting of many tens of layers up to several hundred layers are required. These designs require extensive source material capacities and may mandate multiple, high power deposition sources in a single chamber. In addition, to minimize the deterioration in optical performance resulting from accumulated errors, more stringent deposition controls are required. Precision optics systems are predominately based on diffusion pumps as the high thermal loads can play havoc with the refrigeration units in cryogenic pumps.

Precision optics chambers are often equipped with planetary substrate carriers for better uniformity, but the trade off is an attendant drop in capacity. Severely curved optics (e.g. hemispheres) require special tooling and, in many cases, source location must be optimized for the each of the materials used in the thin film stack. Higher process temperatures are generally required and a typical system will incorporate up to 15 kW of radiant heat. Ion sources have become the enabling technology for precision optics coating, providing a process tool that allows the deposition of moisture stable films and yields better, more consistent thin film material properties such as stress, refractive index, and stoichiometry.

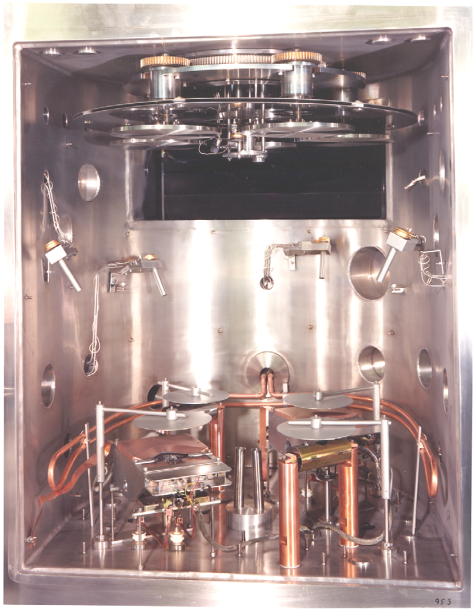


Figure 6: The greater complexity typical of a Precision Optics machine: planetary rotation, multiple QCM sensors and 4 sources.

From a control standpoint, most high precision optical coaters will include a combination of quartz crystal and optical monitors, the former for deposition rate, the latter for end-point determination. The most sophisticated equipment has broad band monitoring capabilities to allow real-time evaluation of the performance of the evolving stack. If errors arise, the remaining layers can be re-optimized to bring the performance back on track.

V. **Summary**:

Increasingly sophisticated equipment users are continually raising the bar in terms of more demanding specifications for system performance in a modern optical coating deposition system. Process issues dictate component selection and chamber configuration in efforts designed to maximize system reliability and process repeatability. The myriad issues involved in designing a plant for optical thin films require system manufacturers to demonstrate skills in the area of process know-how, vacuum technology, system integration and software networking. If the past is any harbinger of the future, this industry will continue to see even greater demands on process control, reliability and intrinsic machine intelligence.