

Considerations and Examples for Determining Precision of Indirect Optical Monitoring

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Abstract

Optical monitoring is the control method of choice for precision optic manufacturers. Advances in control systems over the last decade have made available powerful and convenient components for ease in manufacturing of optical thin films. Never the less, the level of precision obtainable using these systems, is dependent upon other process choices made by the system manufacturer and the thin film engineer. In this paper we discuss these process choices and how they affect precision. Then, using a fully automated optical monitor system, we make a series of coatings where the process control parameters are varied to show the variation in the precision obtainable. Precision in this case will be determined by the computer stored monitor data, data observed by the technician during the deposition and the spectrally measured placement of the measured result.

Introduction

Since the advent of our ability to deposit thin films, achieving accurate control of deposition rate and film thickness has been of utmost importance. This is no less true for optical thin films. Although many techniques have been developed, studied and refined, quartz crystal control and optical monitors have been the primary methods of choice. Quartz crystal monitors have been regarded as best applied for rate control and optical monitors (at least for optical films) the best for thickness control. Even the earliest quartz crystal monitor systems could be used for completely automated deposition systems. In the same time frame, early optical monitor systems were dependent on an operator to make decisions on layer termination. Automated optical monitored systems had to wait for the development of computers. The first fully automated optical monitor controlled coating systems were not available until the latter part of the 70's (late 1977) but was not reported in the literature (this effort was internal to the optical coating facility at Texas Instruments in Dallas) until 1981 (1). This system was reported to achieve a control level equal to that of the best coating technician, higher yields and had better up-time due to fewer mistakes in process sequence steps. Since then, all major optical coating system manufacturers and many of the smaller manufacturers have made automated optical systems available.

The benefits of automation are the ability to simultaneously control many parameters over a short time, reduce cost of hardware and, most of all, reliable precise step sequencing of all actions required in a process at the level equal to or better than that of the best operator. In addition, automated optical monitors make it possible to utilize procedures that would not be possible manually. Examples of this would be broadband monitoring and auto-corrections or re-optimization during the deposition sequence. Of course the latter could be done manually but is quicker and more accurate in a properly design automated system.

Quartz crystal monitors have to be used indirectly and involve an almost linear change of crystal frequency to note film mass accumulation (and thus the film thickness) on the crystal. Optical monitors can be direct monitoring on the parts) or indirect (monitoring a separate chip or chips). In this paper we will concentrate on indirect monitoring where the monitor chips are in the center of the chamber and the parts double rotate in planets around the monitor chip changer. The optical monitor system employed is a classic arrangement where there is a tungsten lamp with a mechanical chopper as the source. This light is then directed through a window on the chamber onto and reflected from a ground back monitor chip through an exit window through an order-sorting filter to the end of an optical fiber. The optical fiber directs the light into a monochromator that is used select a narrow wavelength band and direct the light to a detector. The amplitude of the analog detector signal is then converted to a digital signal and processed by a computer.

Unlike the quartz crystal signal, the optical monitor signal is cyclical, with the value dependent on the refractive index of the substrate, the refractive index of the film material and the phase thickness of the deposited film. An example of the reflectance a high index growing film is shown as the solid line in Figure 1. The amplitude of the repeating cycle depends on the refractive index differences between the film material and the substrate. For the chosen example, a 600 nm film thickness gives a 33% amplitude difference between maximum and minimum signal. The change in amplitude is not linear with thickness. Therefore, the number of turns that the signal must go through and the final signal value is calculated using readily available thin film software. The accuracy of controlling the final film thickness is related to the slope of the signal curve (time rate

of change of signal) which is shown as a dashed line in Figure 1. The least accuracy in terminating a layer would be at the maximum and/or minimum values and the greatest accuracy (least error) midway between the max/min values.

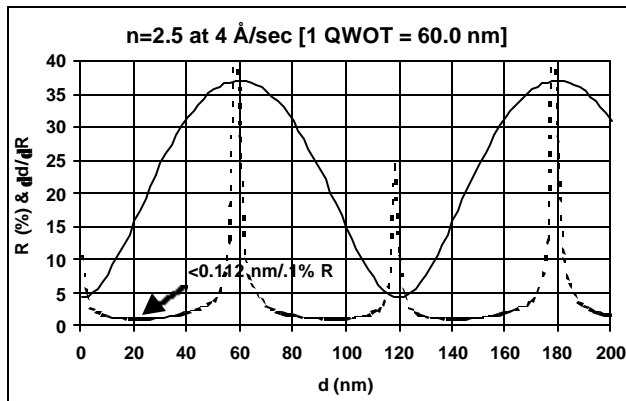


Figure 1. Solid line is the expected signal excursion of a 2.5 refractive index film on a glass ($n=1.52$) monitor chip. Dashed line is the relative error in terminating a layer at the indicated thickness.

In a manually controlled optical monitor deposition, an operator would observe the optical monitor signal, recording start values, maxima and minima and calculating the final signal value for terminating the layer and closing the shutter at the appropriate time. The reaction time of the operator and the hardware involved become a factor in the precision of control. In an automated system, the computer and the computer software take the place of the operator. The choice of hardware and how it is addressed is still a factor. However, one would expect the computer timing factors to be more consistent than a person, thus giving greater precision. The purpose of this study was to determine the precision of the elements of an automated optical monitor system and see how they affect the measured precision of fabricating of an optical coating. In addition, precision for quartz crystal data will be available for comparison. The optical filters being made will be 5-layer and 7-layer calibration band-pass filters since this will give precision for 2 different materials.

System definition

The architecture of the coating system (see Figure 2) used is an Integrity[®] 36 coating chamber with a single 6-pocket E-gun, ion gun for IAD (ion assisted deposition) and a central mounted chip changer. Ion assist levels were sufficiently high so as to make moisture stable films to eliminate humidity variations as a factor in the measured films. All of the control software is in a computer that controls the chamber through a PLC. The computer uses a Cimplicity based package for basic process control with a separate LabView based application for the optical monitor software. Thus the Cimplicity software package sets up the conditions

for controlling the deposition and starts the quartz crystal controller. Once the shutter is opened on instruction from the quartz crystal controller, the LabView OMS (optical monitor software) package records the signal determining max and min values, calculates the final thickness signal value and sends back a "FINISHED" instruction to Cimplicity which directs the shutter to close (via the PLC) and stops the crystal controller.

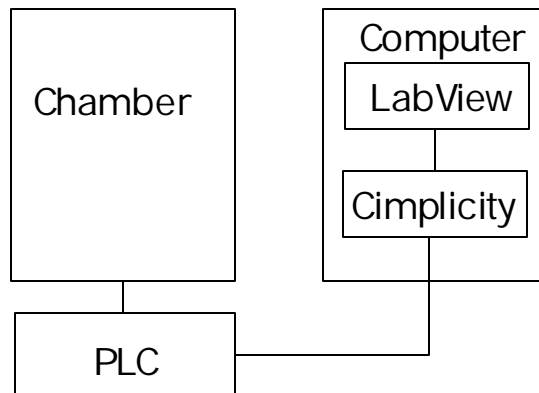


Figure 2. General hardware/software configuration.

Calibrations and Set-up

The materials of choice are TiO_2 and SiO_2 deposited at 4 Å/sec and 5 Å/sec respectively at an average ICD (ion current density) of approximately $140 \mu A/cm^2$. Initial quartz crystal and M:W [monitor to work ratio] calibrations were done using single layer films a QWOT (quarter-wave optical thickness) of about 3 μm . These values were then refined by depositing films which were 2-QWOT thickness at 730 nm, the wavelength chosen to peak the 5-layer [design: HL2HLH] and 7-layer [design: HLH2LHLH] band-pass filters. The initial values of the M:W ratios from the latter runs were 1.38 for both materials. The Essential Macleod software was then used to determine the monitoring scheme.

In order to eliminate cumulative errors as far as possible, monitoring was to be done using layer pairs on the monitor chips starting with the high index material. This gave two possible high index layer thicknesses to be deposited on a bare chip, a QWOT and a HWOT [half-wave optical thickness]. It also resulted in 2 possible combinations for the low index material, a QWOT following a QWOT and a HWOT following a QWOT. The computed signal excursions for the 7-layer calibration band-pass filter are shown in Figure 3. Note that all the high index layers are exactly the same and that the low index layers on chip #1 and chip #3 are the same. Chip #2 has a HWOT low index layer and chip #4 has only the high index layer.

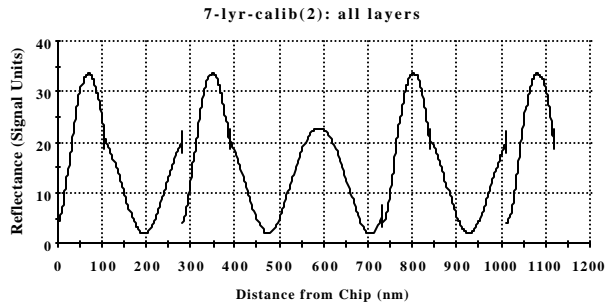


Figure 3. 4 chip monitoring scheme for the 7-layer calibration band-pass filter.

Following (Figure 4) is a copy of the strip chart recording showing the deposition of the above filter.

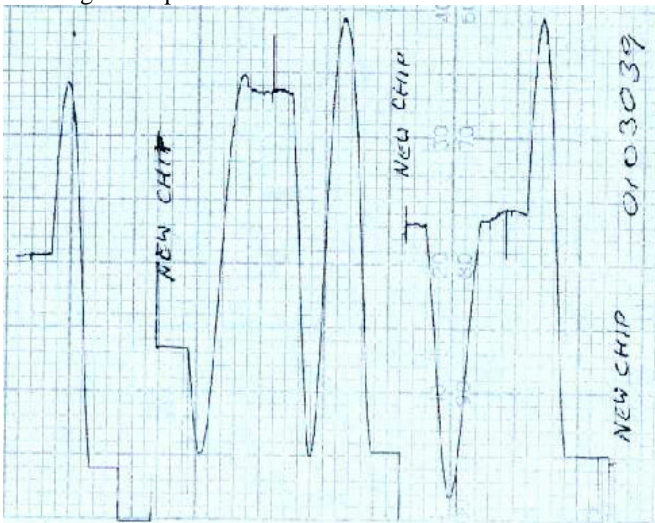


Figure 4. Trace of monitor signal during deposition of a 7-layer band-pass filter. Time $t=0$ is at the right and progresses to the left.

Each design was deposited 5 times, with the OMS precision and the actual precision calculated for each layer. Each filter was also measured to determine the peak wavelength for the band-pass filter. Where there were identifiable problems during the run, data was discarded from the average. Relative to the design scheme, the OMS software for each layer was accurate to an average of 0.02% of the design value and the actual average precision (from data recorded by the technician) was 1.14%. The average peak position for the 5-layer filters [high index spacer] was 742 nm and for the 7-layer filter [low index spacer] was 748.3 nm. Thus the peaks were off by 1.64% and 2.51% respectively from the design value. This is a relatively large amount but not necessarily unexpected since the calibrations were from one single layer test run for each material. The above values can be used to refine the M:W calibrations.

Calculate the peak position for 5-layer and 7-layer BP filters assuming perfect control. Of course the peak $[\lambda_0]$ will be

730 nm. Then vary the thickness of the high index material by a factor of x and calculate the peak positions for the λ_5 and the λ_7 designs. Plot the ratios of λ_7/λ_5 , λ_5/λ_0 and λ_7/λ_0 vs. x [see Figure 5]. The monogram shown in Figure 4 can then be used to refine the M:W ratios as follows:

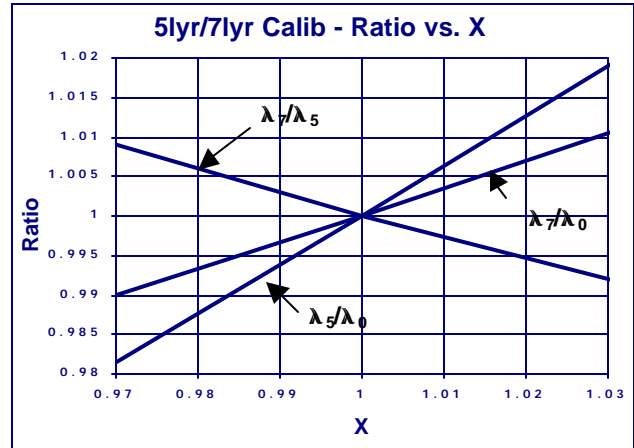


Figure 5. Monogram for M:W corrections.

Find λ_5 [742] and λ_7 [748.3].

Calculate $\lambda_7/\lambda_5 = 1.0085$

Use the monogram to find x [0.972], λ_7/λ_0 [.9905] and λ_5/λ_0 [.983].

Calculate the real λ_0 from the above:

$$\lambda_0 = 748.3/.9905 = 755.5$$

$$\lambda_0 = 742/.983 = 754.8$$

Calculate the new M:W ratios from:

$$M:W_L = (\text{old } \lambda_0) \cdot (\text{old M:W}) / (\lambda_7/\lambda_0) = 1.334$$

$$M:W_H = (\text{old } \lambda_0) \cdot (\text{old M:W}) / x \cdot (\lambda_5/\lambda_0) = 1.373$$

Therefore the new values for the M:W ratios were 1.33 for the SiO_2 and 1.37 for the TiO_2 . These values were used to recalculate the 5-layer and 7-layer calibration BP filters run sheets as had been done before. The new run sheets were then used to deposit each calibration BP filter 5 times and the precision of the OMS software and the actual precision

Table I
[Precision Summary for 5-layer BP]

Run #	Avg OMS	Avg Actual	Peak λ	Deviation from avg.
1	.000117	.0053	730.4	1.5
2	.000075	.0093	727.1	1.8
3	.000049	.0094	730.3	1.4
4	.000080	.0046	728	.9
5	.000114	.0037	728.7	.2
Avg.	.000087	.0057	728.9	1.16

were determined again. These results are summarized in Table I for the 5-layer BP and Table II for the 7-layer BP.

Table II
[Precision Summary for 7-layer BP]

Run #	Avg OMS	Avg Actual	Peak λ	Deviation from avg.
1	.000100	.0045	734.7	.64
2	.000048	.0075	745.2	11.14
3	.000111	.0041	740.7	6.64
4	.000045	.0039	730.4	3.66
5	.000089	.0051	719.3	14.76
Avg.	.000079	.0050	734.06	7.37

Therefore the OMS software was able to calculate the layer termination to better than 0.01% of the layer thickness but the communication delay DDE (dynamic data exchange) rate and hardware response factor resulted in an actual precision of about 0.5% (as compared to the design swing). The 5-layer BP filter peaks fairly close to the design peak 0.16% whereas the 7-layer BP filter peak is much further off, 1%. However this is to be expected. The high index TiO₂ material melts and flows in the pocket providing a very controlled surface for evaporation of the material and therefore a consistent plume of material. The SiO₂ material used was granular in nature and it basically sublimates and does not flow and form a smooth surface. Even though a fresh pocket was used for each layer, during the course of the evaporation, the rate of evaporation from various places in the pocket varied, resulting in tunneling and very poor consistency in the plume. If the material had been deposited from a separate E-gun from a continuously rotating hearth and solid material, it would have been possible to better manage the erosion of the material and would have resulted in much more consistent plume control.

As indicated previously, we also recorded the quartz crystal thickness at the end of each layer. There were four different film thicknesses used in the two designs, a QWOT and a HWOT of each material. Table III shows a summary of the average recorded thickness of each film type along with the average deviation for all the layers of that type as deposited. In addition we compare each to the corresponding optical data for each layer type.

Table III
[Quartz Crystal Data Comparison]

Film	Xtal (Å)	Avg. Dev.	Optical Avg. Dev.
QWOT-H	740	1%	0.5%
QWOT-L	1209	1.5%	0.59%
HWOT-H	1518	.99%	0.28%
HWOT-L	2402	1%	0.34%

References

- 1) D.E. Morton, Delaware Valley AVS Symposium, Cherry Hill, New Jersey 1981.