HYBRID MODE OPTICAL MONITORING

Benefiting from Monochromatic and Broadband Algorithms in the same Coating Process

Broadband monitoring with high signal quality enables use of both broadband and monochromatic layer termination algorithms in the same process when depositing optical interference coatings. Evatec's **Stephan Waldner, Juergen Buchholz**, and **Rico Benz** present case studies using a bandpass filter and an absorbing layer to show how such a "hybrid" approach can lead to the most accurate layer termination.

Introduction

An essential component of state-of-the-art deposition systems for the development and production of optical interference coatings is an in-situ optical monitor. By measuring either transmittance or reflectance on a product or a specific monitor substrate during film growth, the termination of each layer can be controlled based on the actual optical performance of the coating.

While monochromatic optical monitors measure the intensity at a selectable wavelength, broadband optical monitors simultaneously measure the intensity of a large number of wavelengths and therefore allow for monitoring and evaluation of the performance over a wide spectral range. This enables detailed analysis of thicknesses and refractive index dispersions as well as in-situ reoptimization [1,2].

In most cases, both monochromatic and broadband monitoring can be applied, but in certain situations, as shown in the examples below, one of the methods will lead to more accurate layer termination.

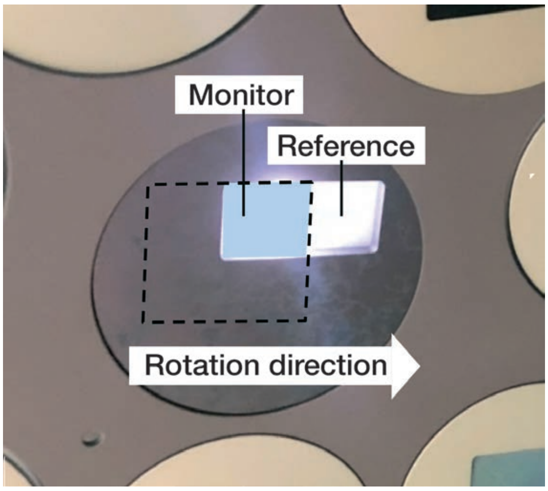

Figure 1. Substrate holder in a Evatec BAK tool with opening for 100% reference measurement

Broadband monitoring with high signal quality

By evaluating just a single or a narrow range of wavelengths from the array detector, a broadband monitor can be used with the same layer termination algorithms as a monochromatic monitor [3,4]. A prerequisite for this is a high signal to noise ratio in order to avoid wrong detection of turning points which would lead to coating failure.

High signal to noise is possible by (a) selection of a spectrometer with a highly sensitive and low noise array detector, (b) optimization of the optical measurement path to eliminate disturbing light arising from the deposition process, and (c) frequent calibration of the measurement. If transmission is measured directly on a substrate moving in the coating chamber, reference measurements can be taken through a small aperture in the substrate holder as shown in figure 1. When the aperture is close to the measurement position, reference and sample measurement are performed within a few milliseconds and therefore fluctuations in the measurement conditions can be greatly eliminated. Transmission is directly calculated as $T_{Mon}(\lambda) = I_{Mon}(\lambda) / I_{Ref}(\lambda)$, where I_{Mon} and I_{Ref} are the intensities measured at the monitor and reference position respectively.

The developments described above have been implemented on both evaporation and magnetron sputter deposition tools using a GSM1101 optical monitor, which covers a wavelength range of 380nm to 980nm (standard version) or 260nm to 980nm (UV extended version).

Hybrid mode optical monitoring

On the basis of broadband monitoring with high signal quality, “hybrid mode optical monitoring” now offers the user the possibility to select between monochromatic and broadband layer termination algorithms for each layer in the design individually. For this purpose the Evatec “Strategy Generator” software loads the coating design and refractive index dispersions and simulates the deposition process. From this simulation, the optimum layer termination criterion and monitoring parameters can be determined for each layer. In the case of monochromatic monitoring, in addition to the wavelength, a width can also be specified to integrate the signal over a narrow wavelength range.

The monitoring data is then uploaded to the deposition tool controller. During deposition itself, the broadband spectra are stored for each layer, even if layers are terminated in monochromatic mode. Engineers that are familiar working with their well know, proven monochromatic monitoring strategies can still benefit from measured and simulated spectra for each layer for analysis, optimization, or in-situ reoptimization.

Application examples

1. Absorbing layer material

Materials suitable for coatings in the infrared region like germanium show a low absorption in the 8µm to 12µm wavelength range. The layer thickness can already be controlled very well by optical monitoring in the visible and near infrared range [5]. Unfortunately, the extinction coefficients vary significantly in that range with deposition conditions and may be difficult to determine.

Figure 2 shows the monochromatic monitoring curve measured in a BAK evaporation system. Due to absorption, the amplitude of the extrema is decreasing. However, by tracking the extreme values and the time between them, the layer termination can be triggered accurately at the intended thickness.

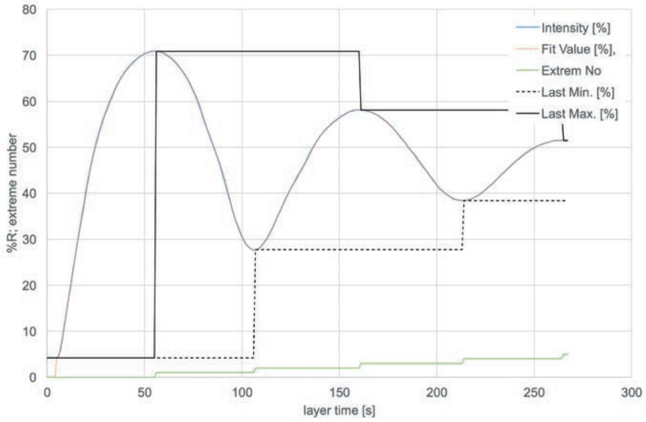

Figure 2. Monochromatic monitor signal (reflectance at 906nm) of an absorbing layer material deposited in a BAK tool.

The MSP

2. Bandpass filters

Example 1 – Simple bandpass filter

As an example for the mixed use of monitoring strategies a simple bandpass filter is considered. The design is made up of 11 layers using TiO$_2$ and SiOs coating materials deposited on float glass. A starting design made of multiples of quarter-waves was optimized to flatten the transmission band. Figure 3 shows the optical layer thicknesses, the design and then the measured transmission spectra.

For this class of designs it is well known that the final filter performance mainly depends on the accuracy of the thick spacer layers. Figure 4 shows the simulated spectra after layers 6 and 10, respectively, where the layer thicknesses of these layers is varied ± 3%. The significant change in the spectrum of layer 6 indicates that broadband monitoring enables accurate layer termination. However, layer 10 shows only a small variation in the spectrum. Here monochromatic monitoring at wavelength 550 nm and layer termination relative to the last minimum and maximum is suitable. Reverse engineering of the deposited thicknesses revealed highly reproducible results for layer 6 (broadband), whereas layer 10 showed a variation of ±1% for the broadband layer termination and less than ±0.1% for monochromatic termination.

Example 2 – Three cavity bandpass filter

A second example is shown in figure 5: the measured transmission of a three cavity bandpass filter in the transmission band from a deposition run monitored with hybrid mode strategy is compared with a run monitored with a pure broadband strategy. This illustrates how the hybrid mode strategy can optimize the pass band regarding symmetry and flatness.

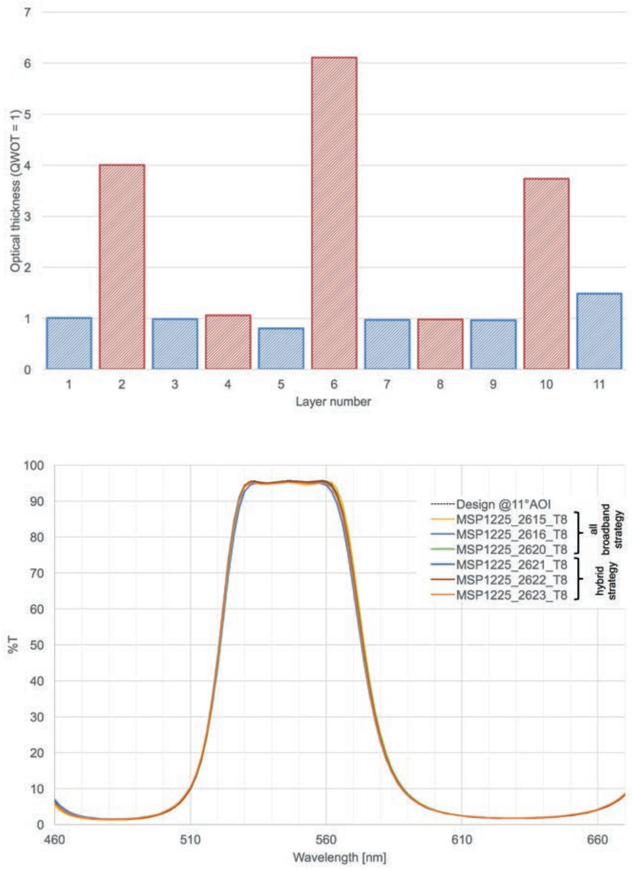

Figure 3. Optical layer thicknesses of the bandpass filter design and transmission spectra of the design and from 6 coating runs.

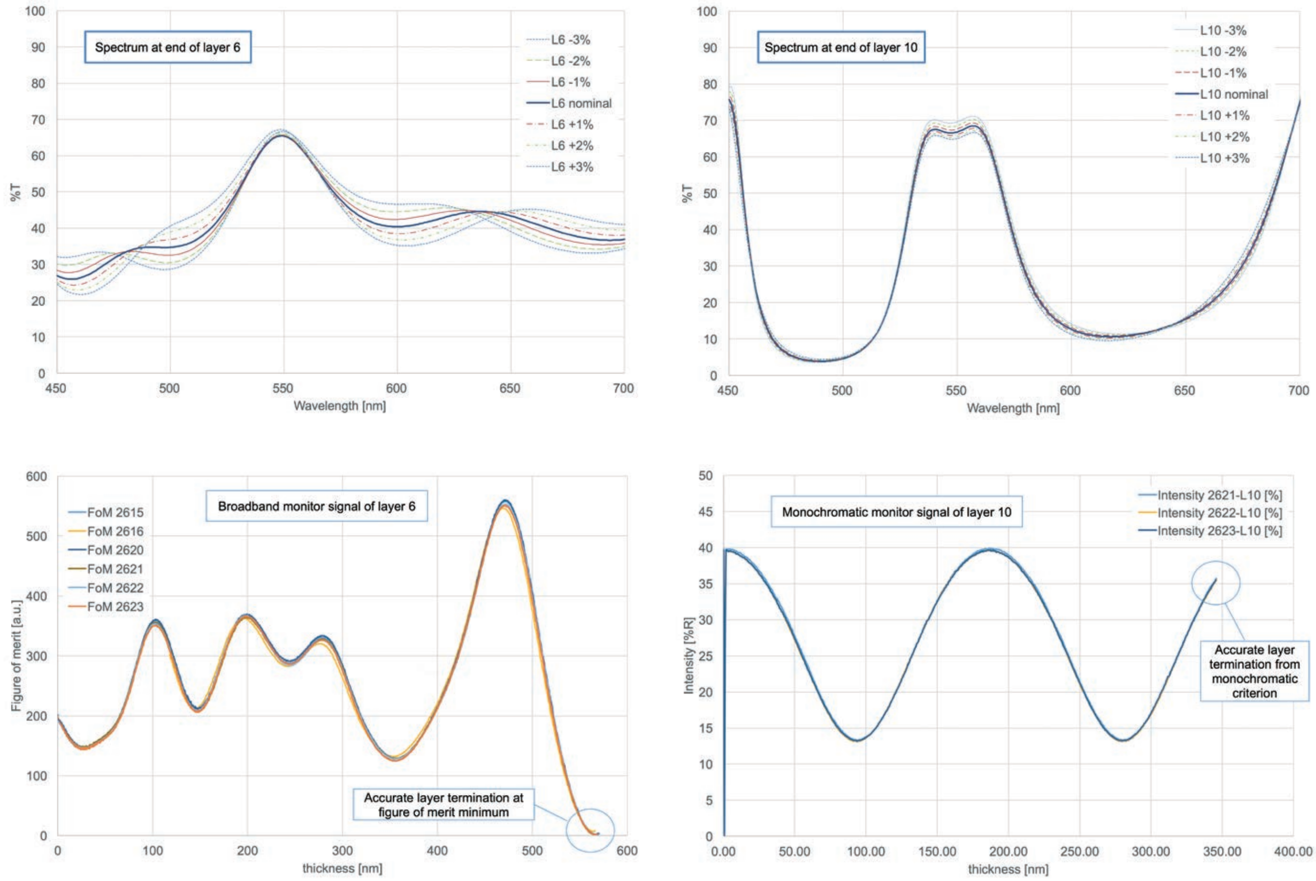

Figure 4. Transmission spectra with thickness variation at the end of layers 6 and 10 and monitoring signals of layer 6 (broadband, 420nm...800nm) and layer 10 (monochromatic, 550nm).

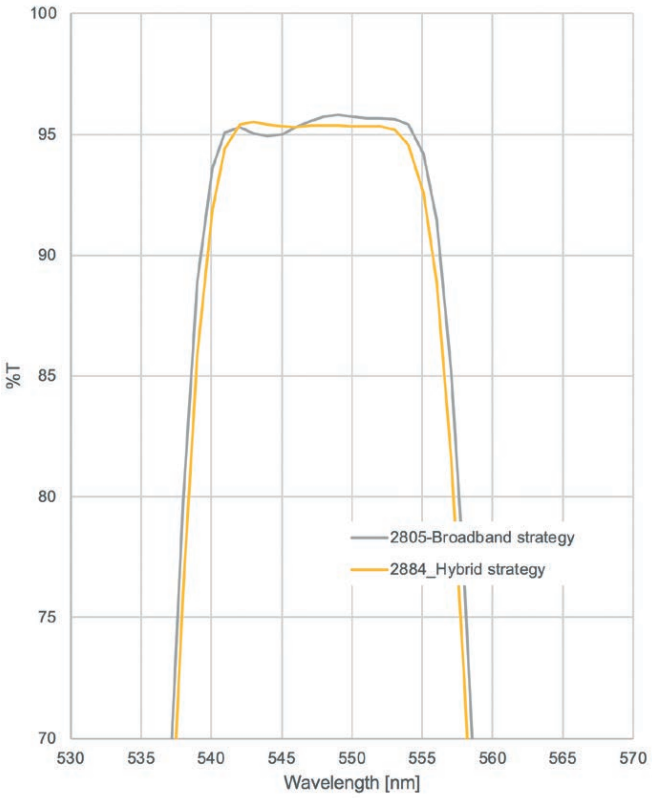

Figure 5. Transmission band of a three cavity bandpass filter monitored with hybrid mode strategy and a pure broadband strategy.

Summary

Hybrid mode optical monitoring combines broadband and monochromatic strategies within the same process. This allows for choosing the most appropriate monitoring method for each layer in a design, which ensures excellent control of the coating processes.

References

[1] Stephan Waldner, Patrick Biedermann, and Silvia Schwyn Thöny, "Online re-optimization of optical filters on a production sputter tool," Chinese Optics Letters **11,** S10207(2013).

[2] S. Schlichting, K. Heinrich, H. Ehlers, D. Ristau, "Online re-optimization as a powerful part of enhanced strategies in optical broadband monitoring", in Advances in Optical Thin Films IV, Proc. SPIE 8168 (2011), 81681E-1.

[3] Stephan Waldner and Jürgen Buchholz, "Versatile Optical Monitoring System with both Broadband and Monochromatic Algorithms" in Optical Interference Coatings Technical Digest 2016, OSA 2016, WC.5.

[4] Alfons Zöller, Detlef Arhilger, Michael Boos, Harro Hagedorn, "Advanced optical monitoring system using a newly developed low noise wideband spectrometer system" in Optical Systems Design 2015: Advances in Optical Thin Films V, Michel Lequime, H. Angus Macleod, Detlev Ristau, eds., Proc. of SPIE Vol. 9627, 962712.

[5] Mordechai Gilo and Daniel Cohen, "Comparison of Broad-Band and Single Wavelength monitoring for IR Coatings" in Optical Interference Coatings Technical Digest 2013, OSA 2013, WB.4.

IMPROVING FILM STRESS AND SURFACE ROUGHNESS

Using a plasma source in magnetron sputtering

Equipping a magnetron sputter deposition system with an additional plasma source enables improvement of surface roughness and film stress independent of the sputter deposition parameters. Evatec's **Silvia Schwyn Thoeny, Silvio Gees** and **Edmund Schuengel** present examples of a HfO_2 / SiO_2 UV mirror and single films of hydrogenated amorphous silicon.

Introduction

High quality optical interference filters typically have to meet a number of requirements, which in some cases are conflicting and cannot all be met at the same time through variation of the sputter deposition parameters.

Using an additional plasma source (PSC), allows the energies of ions impacting the growing film to be tailored independent of deposition parameters. This is due to the turntable configuration of the CLUSTERLINE® 200 equipped with a BPM Batch Process Module. Substrates are exposed sequentially and repeatedly to the sputter and plasma sources.

The potential beneficial effect of using the PSC was investigated for two example cases:

1. HfO_2 / SiO_2 mirror for 355nm: to reduce surface roughness and losses by stray light
2. Hydrogenated amorphous silicon films: to reduce film stress leading to lower warpage of thin 200-400µm substrates of 200mm diameter

Experimental Setup

Thin films were deposited by reactive magnetron sputter inside the BPM equipped with key features for high volume production of precision interference filters including rotating target sources for thickness uniformity < ±0.25%, optical monitoring for high accuracy of individual layer thickness, plasma emission monitoring PEM for high deposition rates and automatic substrate handling for high productivity.

The PSC with grounded grid generates an asymmetric magnetized capacitively coupled plasma. Ion energy and ion flux can be controlled by source parameters including power level, gas flow and magnetic field of the two coils.

Characterization of the PSC was done by Retarding Field Energy Analysis (RFEA), Faraday cup and optical emission spectroscopy. An RFEA sensor was placed on the turntable and set to coincide with the center axis of the PSC as shown in figure 2.

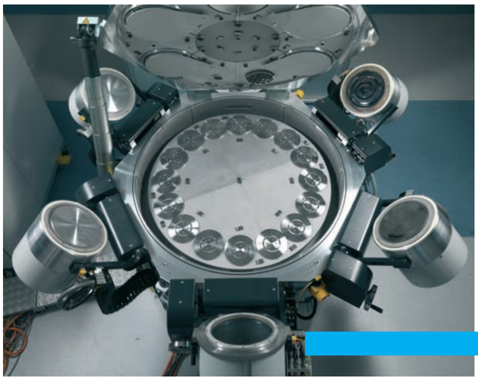

Figure 1. CLUSTERLINE® 200 system equipped with BPM with 4 sputter and 1 plasma source

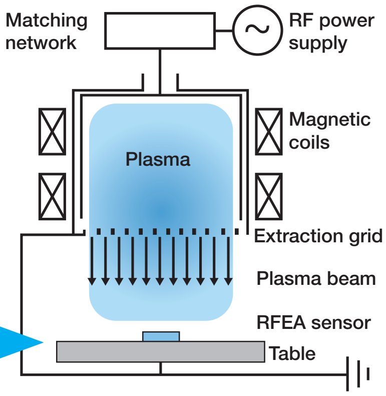

Figure 2. Capacitive coupled plasma source (PSC)

Results

Characterization of the Plasma Source (PSC)

Figure 3 shows the Ar ion energy distribution measured by the RFEA for specific settings of the process parameters of the plasma source. However the curve is representative of all parameter combinations.

- Charge-exchange collisions in the “field-free zone” between the PSC grid and substrate cause a peak at low energies
- We see a double (bimodal) peak due to ions arriving on the substrate without collisions
  → these ions carry the energy needed for process enhancement.

Since the RFEA measurements cannot be done during a process a measure had to be found which was indicative of the ion energy. Figure 4 shows a very good correlation of the average ion energy determined from RFEA with the DC self-bias measured by the PSC power supply. The data were taken over a large variation of process parameters such as RF power, gas flow, coil currents etc.

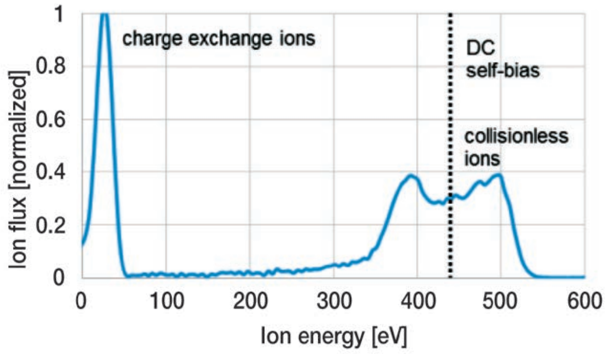

Figure 3. Ar ion flux-energy distribution

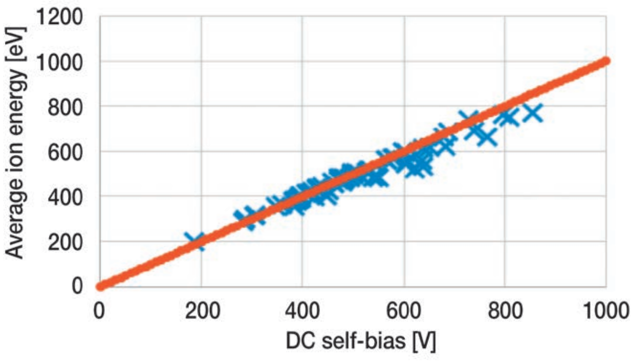

Figure 4. Average ion energy vs DC self-bias

Influence of Plasma Source (PSC) on surface roughness

The material combination SiO_2 and HfO_2 was chosen due to its known tendency to form rough surfaces and the wavelength of 300-400nm because stray light effects are stronger at shorter wavelength.

SiO_2 PSC	HfO_2 PSC	Loss at 320nm [%]	AFM Ra [nm]
No	No	3.82	2.0
No	Yes	3.31	1.8
Yes	No	2.36	0.6
Yes	Yes	2.38	0.4

Table 1. Process conditions and results of UV mirror coating

Figure 5 shows a clear reduction of the surface roughness from Ra=2nm to 0.4nm if the mirror is deposited with PSC assist for both materials. For those samples the losses are strongly reduced as determined by photospectrometric measurements evaluated in the edge zone of the mirror, where losses are enhanced due to resonance effects. A reduction in surface roughness leads to a clear reduction of losses due to stray light.

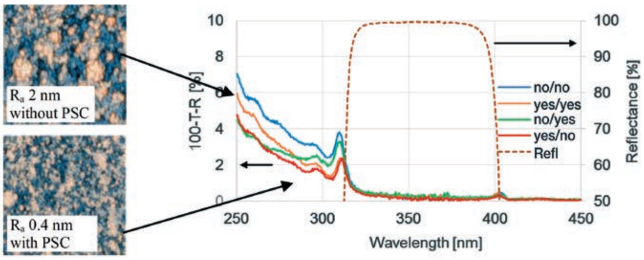

Figure 5. Losses and reflectance of UV mirror with deposition of layers with / without PSC according to table 1 above.

Influence of Plasma source on film stress

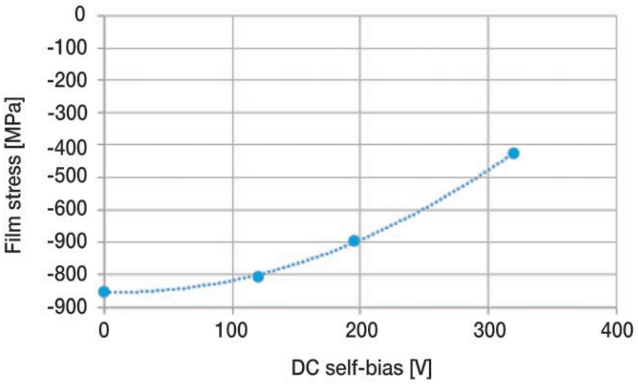

Figure 6. Stress of aSi:H single layers as a function of ion energy (dotted line to guide the eye)

Figure 6 shows that the film stress of hydrogenated amorphous silicon (aSi:H) single layers can be strongly reduced as a function of the DC self-bias. In multi criteria process optimization it is a major advantage if stress can be influenced independently of the sputter deposition parameters.

Summary

- DC self-bias indicated by the PSC power supply represents the mean ion energy
- The UV mirror shows a strong reduction of surface roughness and stray light losses through use of a PSC
- Film stress can be tailored by use of a PSC as shown using the example of amorphous silicon