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Industrial-scale deposition of highly uniform and precise optical interference filters by the use of an improved cylindrical magnetron sputtering system

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ABSTRACT

The manufacture of precision optical interference coatings requires a process with sufficient accuracy, precision, uniformity, and stability to produce economic quantities of coatings with acceptable yield. This paper compares the capabilities of the plasma assisted reactive magnetron sputtering (PARMS) process with the compound-assisted reactive sputtering process (CARS). Compared with PARMS, CARS exhibited superior process accuracy, stability and uniformity by being less sensitive to equipment and process temperatures, and to cathode and machine conditioning. A uniformity deviation of less than ±0.15% is demonstrated for different optical multilayer filters over substrates of 200 mm diameter. The CARS process stability and precision are also demonstrated using many coating runs of a sensitive, broadband antireflective coating without the need for optical monitoring. Thus, it is shown that CARS combines the advantages of the Metamode (high stability) and the PARMS process (low optical absorption).

1. Introduction

The development of new deposition techniques has always been an ongoing challenge in the optical industry. Driven by market and technological needs, requirements have been increasing continuously over recent years. Products for the optical telecom industry need tolerances of less than ±0.01% or ±0.001% with product sizes of only a few mm^2. Smaller lenses with diameter of approx. 20 cm call for tolerances of about ±0.4% or less [1]. High-precision optical filters have been commercially available for many years now. Pushed by telecom applications such as dense wavelength division multiplexing (DWDM) filters or gain flattening filters (GFF) [2], filters with high optical performance, compensated optical stress and high environmental stability have been demonstrated and transferred into other applications such as the life sciences, spectroscopic instrumentation, medicine, the consumer industry and others. Magnetron sputtering batch coaters represent an important development in the area of flexible and high-precision optical coating machines [3–5]. Dense, high-precision optical filters containing hundreds or even thousands of layers have been demonstrated using magnetron sputtering technology [6,7], and shown to be a promising concept for the production of highly advanced optical filters.

From an economical and also a technical viewpoint, the deposition process of multilayer optical precision coatings must be able to guarantee a constant uniformity throughout the whole production cycle, i.e. if possible throughout the target lifetime. This requires layers with uniform thickness with no drift or dependence on the position in the deposition system.

For the production of filters, a stable uniformity and precision have a high importance. Rotating turntable coating turned out to be a very suitable process since it combines a high throughput with excellent layer properties. Different processes have been investigated in the past, such as full reactive sputtering, plasma-activated reactive sputtering [8] or metalmode sputtering with plasma oxidation (Metamode) [9] process.

Recently a new sputtering system has been presented [10,11], where instead of planar magnetrons, cylindrical rotatable magnetrons have been implemented in a double magnetron setup. The main advantages of this system are very clean, particlefree coatings [12] and a constant erosion profile on the sputter cathode. Recently it has been shown that by working in PARMS (plasma-assisted reactive magnetron sputtering) mode with that configuration, highly uniform layers can be produced. In a PARMS process, a metallic target is used and additional reactive gas is supplied into the sputter compartment, so that a substoichiometric layer results. A successive oxygen plasma source which is locally separated from the magnetrons make it possible to obtain fully stoichiometric and transparent films. However, a long conditioning time was necessary in [13], which was attributed to conditioning effects of the system in combination with a partially reactive sputter process even with low oxygen content.

In a reactive sputtering process stability is a key factor for high precision. It is well known that by separating oxygen from the target,

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process stability can be increased significantly. The Metamode process [9] is based on this principle.

In order to improve the stability of the system, in the present paper a modified deposition process is demonstrated which uses compound sputter targets in combination with a plasma source for oxidation for the high index layer. This process is defined as CARS (compound-assisted reactive sputtering). The stability of the uniformity was investigated during the production of interference filters.

2. Experimental details

2.1. Deposition system and deposition processes

The setup of the coating system (EOSS) is depiced in Fig. 1 and the details of the sputter compartment are shown in Fig. 2. Technical details about the deposition system are described in [10,11], so only the essential details are given here. The system is based on a rotating turntable system in a sputter up configuration (the substrate is face down). The coatings are always deposited in a dynamic mode with continuously rotating turntable. The turntable speed is always 250 rpm. Two cylindrical double magnetrons (Sputtering Components Inc.) with a target length of 550 mm are installed in the system. For the low index material, SiO_2 was used. Two silicon-sprayed targets were employed. Ta_2O_5 and Nb_2O_5, respectively, were used as high index material. Ceramic TaO_x and NbO_x and metallic tantalum targets were used. The Ta_2O_5 layers in the PARMS process were deposited with an oxygen partial pressure of 2×10^{-5} mbar in the sputter compartment. During these experiments the plasma source was always run at a power level of 3 kW. Only oxygen was used as process gas for the plasma source. The dynamic deposition rate, measured with continuous rotation of the substrates, was between 0.3 and 0.6 nm/s depending on the process setpoint. The target power was 6–10 kW per double magnetron. Process power is delivered by 20 kW mid-frequency (40 kHz) generators (Hüttinger Truplas). The total pressure in the sputter chamber for all materials was around 5×10^{-3} mbar. In the case of the PARMS process, a λ-probe sensor (Zirox GmbH) was used to monitor the oxygen partial pressure. In the case of Metamode sputtering (i.e. without additional oxygen gas in the process chamber) no additional gas sensor was needed. This was also the case for the CARS process. In the CARS and Metamode processes as well, the plasma source was run with same process parameters as used for the PARMS process. A low particle contamination of the coatings was demonstrated in [13]. A substrate cabinet with 12 carriers is used to store the substrates to be coated. Each carrier can hold substrates with up to 200 mm in diameter. The monitor test glass wafers, which are used for the broadband optical monitoring, are also stored in the cabinet on a special monitoring carrier. The test glasses are synthetic quartz substrates (25×65 mm^2) 1 mm thick, each one mounted on its own carrier. With the 12 carriers, up to 11 different monitor test glasses can be exchanged automatically during a coating cycle without breaking the substrate cabinet vacuum. Afterwards the substrate cabinet can be vented separately from the process chamber to allow the exchange of test glasses. The optical monitor is based on a fiber-optic spectral transmittance monitor continuously from 350 to 1600 nm. As monitor and control software, the Modular Optical Coating Control Application (MOCCA$^{+®}$) developed at Fraunhofer IST was used. Further details can be found in [11].

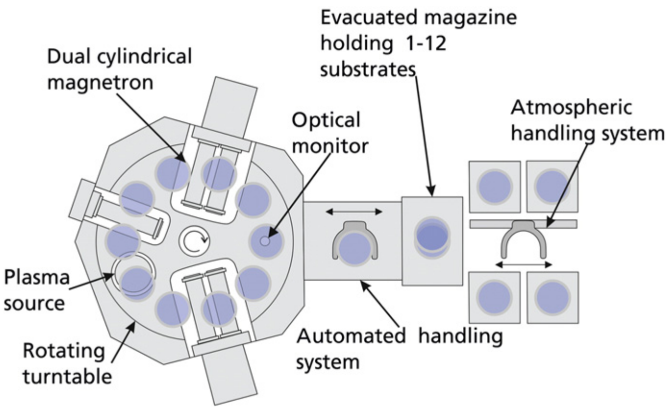

Fig. 1. Scheme of the deposition system used for the experiments.

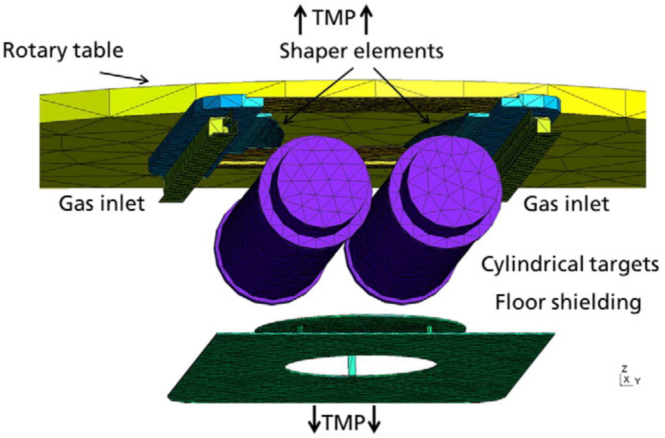

Fig. 2. Sputter compartment used for the experiments [14].

2.2. Sample analysis

The refractive index of the films was measured by spectroscopic ellipsometry (model Senresearch, Sentech Instruments GmbH). This instrument also was employed for the thickness uniformity measurements on the single films. Films 300 nm thick were deposited on B270 glass substrates. Although the software is able to cover backside reflections, a micro spotlight was used to mask out the reflection of light from the backside of the substrate. The back was roughened as well. The accuracy of the ellipsometric thickness measurement of the 300 nm thick Ta_2O_5 layers was estimated to be within ± 0.15 nm (i.e. $\pm 0.05\%$). For the deposition of the filters, the refractive index dispersion was fine-tuned by using in-situ transmittance spectra from filter coatings. This is necessary, not because of an unsatisfactory determination of the refractive index by ellipsometry or by transmission, but due to very slight variations in the refractive index during the deposition process of the filters which were caused by the growth processes or by temperature effects.

The uniformity of the filters along and normal to the direction of movement was determined from the wavelength of a typical feature of the coating, e.g. the 50% transmission value of the band-edge. For this purpose the optical broadband in-situ monitor and MOCCA^{+}® were used. Also a Perkin Elmer 950 spectral photometer was also employed for measuring the reflectivity and transmission of other samples.

It should be pointed out that for the uniformity analysis of single films and of the filters, no significant influence of the refractive index on the measurement position on the substrate (center, outside) was found. On the basis of the accuracy of the instrument, refractive index variations are less than 0.005. A fixed dispersion formula of $n(\lambda)$ was used to analyze non-uniformity.

3. Results and discussion

3.1. Uniformity of single films

In this section, three different processes are investigated: PARMS, Metamode and CARS. The initial process was the PARMS process, which was used in Figs. 3 to 5. Fig. 3 shows the optimized uniformity