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Progress on optical coatings deposited with dual rotatable magnetrons in a sputter up system

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ABSTRACT

A turntable magnetron sputter system based on cylindrical magnetrons was used to investigate particles and uniformity profiles of different processes and coatings. The sputter system is based on a dynamic deposition employing a high-speed turntable and a double cylindrical pulsed magnetron discharge for the deposition of low and high index layers. Contamination by particles was investigated for different processes. Very clean coatings could be obtained for single layers as well as for multilayers. The thickness uniformity was investigated and optimized. In partial reactive mode, the oxygen partial pressure distribution is influenced by getter effects of the different surfaces in the sputter compartment, which makes the optimization of the uniformity more difficult. After suitable conditioning of the coater, a reproducible uniformity of 99.6% overall the substrate area was observed. The slope of the non-uniformity can be modified by changing the angle of the magnet bars of the magnetrons. The deposition of an optical multilayer system with around 60 layers and a total thickness of 8 μm was demonstrated and also a uniformity of 99.6% could be determined on different 200 mm glass substrates perpendicular and parallel to the arc of motion.

1. Introduction

For several decades, high precision optical filters have been industrially applied. Pushed by the telecom applications such as dense wave division multiplexing (DWDM) filters or gain flattening filters (GFF) [1], filters with high optical performance, compensated optical stress and high environmental stability have been demonstrated and transferred into other applications such as life science, spectroscopic instrumentation, medicine, consumer industry and others. The ever increasing demands on individual optical interference coatings of high quality are an ongoing challenge. Magnetron sputtering batch coaters represent one of the developments in the area of highly flexible and high precision optical coating machines [2–4]. Dense, high precision optical filters containing several hundreds and even thousands of layers have been demonstrated using magnetron sputtering technology [5,6]. From an economical and also from a technical view, 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 optical constants without any drift or dependence on the position in the deposition system. Tilsch et al. [7] discussed recently the requirements regarding precision, i.e. the allowed spectral tolerance for coatings. According to [7], they are ranging from about ±0.4% or less for smaller optics (ca. 0.2 m in diameter) and less than ±0.01% or ±0.001% for telecom products of only some mm^2 size. However often also for such small products it is required to deposit on larger area to reduce cost.

Common sputter systems for precision optics are typically working with planar magnetrons, either in a linear or in a round shape. To obtain high deposition rates, mostly reactive pulsed magnetron sputtering is used. Therefore, either single cathodes (unipolar sputtering) or double magnetrons (bipolar sputtering) are common. In reactive sputtering with the use of a metallic target, oxygen is added to obtain stoichiometric, transparent layers. In a standard magnetron with static magnetic field arrangement, the sputtering from the target takes place in a defined region where the parallel component of the magnetic field is maximal. In the other regions of the target, back sputtering occurs, which means that sputtered target atoms together with oxygen gas will form oxide which will be redeposited outside the racetrack but on the target area (see Fig. 2). In some cases, especially for highly isolating oxides such as SiO_2, this leads to arc discharges connected with the creation of particles and defects in the film [8–11]. In addition, planar targets suffer from inhomogeneous erosion due to the formation of a racetrack [8].

Approaches such as the CleanMag™ concept [12] or, in the case of a planar round target, rotating magnets have been developed in the past to reduce contamination by particles. There, the magnets are moving in order to influence the plasma density and thus the layer properties such as the particle contamination.

To overcome these problems in precision optical coatings, a new sputter system has been presented [13,14]. Instead of planar magnetrons, cylindrical rotatable magnetrons have been implemented in a

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double magnetron setup. Shortly after the expiration of the patent protection of Scobey et al. [15], these cathodes have successfully been introduced into coaters for production of large area coatings some years ago [16–20]. However, to our best knowledge they have not been used in precision optics so far. While the main reason for the success in large area production was the much higher cost efficiency [21] of these cathodes, in precision optics other factors are even more important such as the intrinsic stability and cleanness of the coating process as well as the layer properties. In reactive sputtering process stability is a key factor for high precision. It is well known that by separating oxygen from the target, process stability can be increased significantly. The MetaMode ™ process [21] is based on this principle. In the present paper, a partial reactive sputter process in combination with a successive radiofrequency (13.56 MHz) plasma oxidation was used to deposit the high index Ta_2O_5 layer. A high gas separation between the sputter area and the plasma source was realized. In the present paper, the deposition process was investigated especially with respect to particle generation and uniformity of the coatings.

2. Experimental details

2.1. Deposition system

The principle scheme and more technical details about the deposition system can also be found in [13,14]. As shown in Fig. 1, the coater is based on a rotating turntable system in sputter up mode (substrate face down). Two double magnetrons (Sputtering Components Inc.) with a target length of 500 mm are installed in the system. Metallic Si targets and Ta targets were used. Process power is delivered by each 20 kW mid-frequency (40 kHz) generators (Hüttinger Truplas). The target–substrate distance was around 80 mm. In the case of reactive sputtering, a λ-probe sensor (Zirox GmbH) was used to control the oxygen partial pressure. A substrate cabinet with 12 carriers is used to store the substrates which have to be coated. Each carrier is able to hold substrates with up to 200 mm diameter. Also the monitor test glass wafers, which are used for the broadband optical monitoring, are stored in the cabinet. The test glasses are synthetic quartz substrates (25×65 mm^2) with 1 mm thickness, each of them mounted in a separate carrier. With the 12 carriers, up to 11 different monitor test glasses can be exchanged automatically during a coating cycle without breaking the vacuum conditions. To change the test glass carrier, the turntable rotation has to be stopped. The optical monitor is based on a fiber optic spectral transmittance monitor working from 350 to 1600 nm. For the filter shown in Section 3.4, a spectral range between 350 and 1100 nm was applied for control. As monitor and control software, a modular optical coating control application (MOCCA$^+$) was used. It is able to communicate with the Optilayer software [22], i.e. Optilayer designs can be loaded into the software and vice versa. The software determines the deposition rate from the thickness determination of the growing layer from the optical spectral transmittance spectrum. The coating is stopped also by a signal from the software. After each completed layer, a reverse engineering step can be performed after each layer automatically, i.e. an optimization step is used wherein the thickness of the residuary layers will be optimized to reduce coating errors. However in this paper this option was not needed. For the 60 layer filter presented below, one test glass change has been undertaken. The coatings are always deposited in dynamic mode, i.e. with rotating turntable. The turntable speed was 250 rounds per minute. SiO_2 and Ta_2O_5 were used as low index and the high index material, respectively. For the particle analysis of a multilayer filter (see Section 3.2), Nb_2O_5 from a ceramic NbO_x target has been used as high index material. SiO_2 and the Nb_2O_5 layers were deposited in the MetaMode process without oxygen in the sputter compartment. The Ta_2O_5 layers have been deposited in a partial reactive mode with oxygen in the sputter compartment with an oxygen partial pressure of 2×10^{-5} mbar. The dynamic deposition rate, measured with continuous rotation of the substrates, was between 0.3 and 0.6 nm/s depending on the process set point. Target power was 6–10 kW per double magnetron (mid-frequency, 40 kHz).

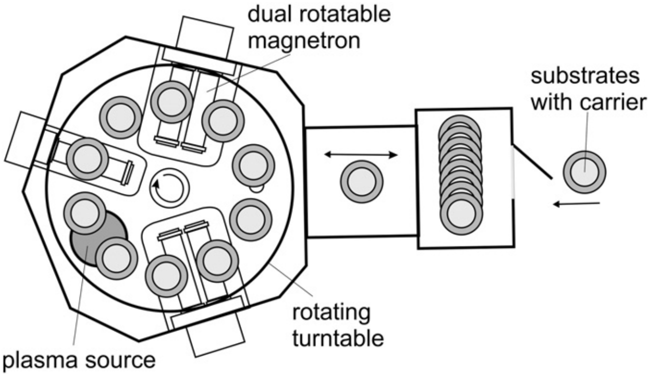

Fig. 1. Scheme of the deposition system used for the experiments.

2.2. Sample analysis

The film stress of the samples was determined by measuring the curvature change of coated thin glass (Schott D263T, size 100×10 mm^2, thickness 100 μm) by laser optical triangulation. The mechanical film stress is calculated employing the Stoney-formula. The method is described in [31] and it has been shown there that it is comparable to other methods which employ silicon wafers or fused silica substrates in combination with interferometry.

The refractive index was measured by spectroscopic ellipsometry (model Senresearch, Sentech Instruments GmbH). Also the optical transmittance was used to determine the absorption index of the films. Therefore a Perkin Elmer 950 spectral photometer was employed.

For the particle analysis, the coatings deposited in the present paper were compared with coatings formerly deposited in a sputter down system [24]. The latter is also a turntable coating system with dual magnetrons. These coatings were made in a reactive process from metallic targets. In this case, the turntable main rotation is slow (<5 rpm) but it has a sub rotation of the substrates. Also the substrates were loaded into the process chamber with the use of a robot handler. While in the present paper the samples are handled in a clean room, in [24] a flow box (quantified class 1000 according to US FED STD 209E clean room standard) was installed in front of the handler. The flow box itself as well as the whole equipment are placed in a normal laboratory environment with filtered air. A soft pump system was installed in [24] to reduce pressure surge. The substrates were packed in a twofold wise. The outer package was used to transport the samples in laboratory atmosphere while the inner package was used in clean room atmosphere only. In both deposition systems, the handling level was determined before and after each deposition run in order to avoid additional errors.

3. Results and discussion

3.1. Layer properties

The main focus of the paper is not the investigation of layer properties, so only basic information is given here. The layers are amorphous as proved by x-ray diffraction measurements. The dense structure is shown in the SEM picture (Fig. 2). No spectral shift was observed after venting the coater. For SiO_2, the refractive index was determined as 1.485 at 550 nm. For Ta_2O_5, the refractive index was 2.195 at 550 nm. The film stress was in the range of 200 to 400 MPa (compressive) for SiO_2 with a film thickness of 150 nm. For Ta_2O_5, the stress was 150 MPa (500 nm thickness) and 200–300 MPa (150 nm thickness). Taking into account the thickness dependence of the film stress, these values are very comparative to values determined by a plasma assisted