Plasma Assisted Reactive Magnetron Sputtering of Demanding Interference Filters

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ABSTRACT

Plasma assisted reactive magnetron sputtering is used successfully for more than 10 years to produce demanding interference coatings that cover a broad spectral range from the VUV to NIR by using different oxides as coating materials. The use of a spatial separated plasma source from a traditional reactive magnetron sputtering environment and fast substrate transportation between both regions allows precise control of layer properties. Using planar mid frequency powered dual magnetrons allows producing very low absorbing films with high deposition rates. The use of co-sputtering with two materials can create intermediate refractive indices and layers with low intrinsic stress. Using radio frequency powered magnetrons can improve the layer quality in respect to achievable stress levels, defect density and laser induced damage threshold. Direct monochromatic wavelength monitoring enables the control of the optical thickness of the growing films very precise at wavelength from the UV to the NIR. Using the optical monitoring to calculate the deposition rate constantly during the production of a thick interference filter allows the use of thin layers that are avoided normally. Changing the test slide for direct optical monitoring during the deposition allows the more simple set up of monitoring strategies and avoids error accumulation. Combining process and monitoring technology allows the fast production of demanding interference filters with large layer number and high total thickness.

INTRODUCTION

Plasma assisted magnetron sputtering (PARMS) uses for the production of dielectric layers an additional plasma source to achieve superior layer qualities. But on contrary to Ion assisted Deposition (IAD) or plasma ion assisted deposition (PIAD) the main role of the plasma source is not the densification of the coating, but to run the sputtering process in a more favorite process condition and to minimize the absorption losses of the deposited coating material. The densification of layer is done by the sputtering process itself. A high gas separation between the plasma source and the sputtering compartment is essential to run the sputtering process at a stable working point with high constant deposition rates and with a predictable stoichiometry. Various methods exist for an active control of the working point, like the voltage control of the sputtering discharge, plasma emission monitoring of selected emission lines of the sputtered elements or partial pressure control by the so called lambda sensor. The usage of dual magnetrons is favorable due to there excellent long term stability and the achievable high deposition rate. In some cases single cathodes are used, which is favorable for achieving lower substrate temperature, lower intrinsic stress or lower defect levels.

SYSTEM LAYOUT

Figure 1 shows the basic layout of a PARMS system. The substrates are mounted on a substrate carrier and loaded via a load lock into the turn table of the sputtering module. The sputtering sources and the plasma source are located above the horizontal rotating turn table. Each source is pumped separately and the mechanical slits between the process compartments are minimized to achieve a high gas separation value. The substrate temperature can be adjusted by a back side heating element. One of the substrate positions is used for optical monitoring in a wide wavelength range. The monitoring can be done in transmission or reflection, single or wide band monitoring is possible. The turntable rotates with more then 200 rpm. At each pass beneath the cathode only a very thin none stoichiometric layer is deposited. A pass beneath the plasma source is used as a next step to add the missing reactive component and thereby to assure very low absorbing films. Details of the system layout are given in references [1, 2]. Details of the monitoring system can be found in reference [3].

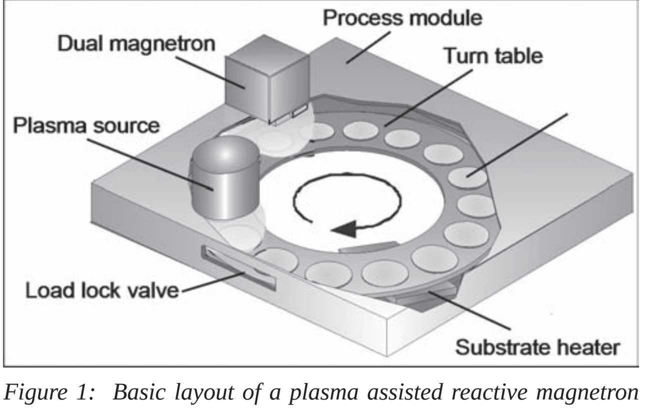

Figure 1: Basic layout of a plasma assisted reactive magnetron sputtering (PARMS) system.

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LAYER PROPERTIES

Table 1 gives an overview about the achievable refractive indices, stress levels and rates of selected materials. The rates are the mean values on the whole turntable. The low stress level of the hafnia and the zirconia films are achieved by co sputtering together with silica. Details can be found in references [4, 5]. By using co-sputtering of nioba and silica any refractive index between the two extremes of the pure material can by created as is be shown in Figure 2. All materials deposited with PARMS technology exhibit very low extinction coefficients without any post treatment of the layers. Absorption values of the tabulated oxides at a wavelength of 1064 nnm with lambda optical thickness are in generally below 10 ppm. All dielectric mirrors with reflection values of more then 99.99% on super polished substrates have been achieved, showing the capabilities for low scattering losses in the deposited films.

Table 1: Properties and achievable rates of selected oxide materials deposited with PARMS.

Material	Refractive index n @ 550 nm	Film stress [MPa]	Deposition rate [nm/s]
SiO_2	1,48	- 100	0,45
Al_2O_3	1,67	- 115	0,4
Nb_2O_5	2,365	- 150	0,5
Ta_2O_5	2,166	- 90	0,6
ZrO_2	2,13	- 70	0,5
HfO_2	2,075	- 170	0,5

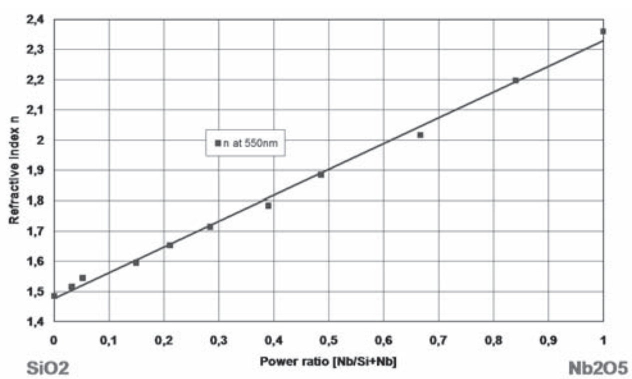

Figure 2: Refractive index vs. power ratio of co-sputtered $Nb_xSi_yO_z$ layers.

INTERFERENCE FILTERS

The main purpose of the HELIOS machine is the production of demanding interference filter with high layer number and tough request in respect to film thickness and optical constants. Depending on the filter design the multilayer stack is controlled by optical monitoring, time control or a combination of both. The monitoring can be done on one or multiple monitoring substrates. By choosing different light sources and detectors a wavelength range of 210-1700 nm is accessible. The challenge is to achieve a very high signal to noise ratio despite the short measurement time off a few milliseconds due to the high speed of the turn table. Even designs with more than 200 layers and thicknesses above 20 µm have been produced in a full automated process. Examples of Notch filter, chirped mirrors and band pass filter that showing a high degree of coincidence between design and experiment have been published in references [6, 7]. Extending the application range from the VIS to the UV is a challenge, because of limited material choose, difficulties in achieving low extinction coefficients and setting up a precise working optical monitoring system. The achieved result of a 6 cavity band pass filter for a wavelength of 212 nm can be seen in Figure 3. As materials silica and alumina were chosen. The filter was monitored direct at the desired wavelength. The good performance shows that the application range of PARMS can even by extended to this low wavelength.

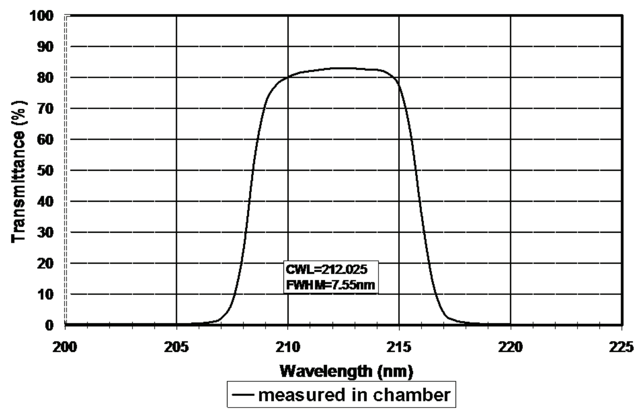

Figure 3: Band Pass Filter for 212 nm, 6 cavity design, 90 layers Al_2O_3 and SiO_2.

LASER COATINGS

Beside low extinction coefficients of the deposited materials the achievable laser damage threshold of the coated substrate is a very important parameter for qualifying laser coatings. The low absorption values achieved with PARMS qualify them in principle for achieving a high laser induced damage threshold (LIDT). The use of a load lock system is an advantage against batch systems without one. But care has to be taken, that defects are not create within the coating chamber by plasma arcing or debris from parasitic coated chamber parts. Minimizing thermal expansion of coated parts by good cooling, a good surface roughness of all chamber parts and low intrinsic coating stress of the deposited layers are essential.

With standard process using $HfO_2/ZrO_2/SiO_2$ as deposition material, LIDTs far above 100 J/cm^2 have been achieved for HR mirrors (1on1 LIDT @ 1,064 nm, pulse length of 8 ns, 1/e^2 beam diameter of 185 µm). The layers were deposited from dual magnetrons with metallic targets. The achieved compressive stress levels in the coatings for were -350 Mpa for SiO_2, -410 Mpa for ZrO_2 and -1000 Mpa for HfO_2. Details can be found in reference [2]. To improve the stress level of the high index materials co-sputtering with Silica can be used. Thereby the compressive stress of Hafnia and Zirconia could be lowered to -170 Mpa respectively -70 Mpa while a high deposition rate of 0.5 nm/s could be maintained [4, 5]. By changing the gas composition in the silica process it was possible to reduce the compressive stress in the silica to values of -100 Mpa. This was accompanied by a slight decreased of the deposition rate from 0.45 to 0.33 nm/s.

To investigate the defect level in the coatings optical inspection of 1 µm thick single layers were executed. The layers were deposited on silicon wafers as substrates and were inspected with a Leica DM 4000 M microscope in dark field illumination. Do determine the defect concentration in the coating by the back scattered light the samples were scanned and the pictures were analyzed by an image processing and defect recognition software. The defects were classified regarding there size and defect density and sorted into 4 groups of, 2-5 µm, 5-10 µm, 10-20 µm and greater 20 µm. The actual measured size was influenced be the threshold levels, set in the recognition software. However, by comparing individual defects in bright and dark field illumination it was found that the bright field diameter of defect was always smaller than the determined one in the dark field. For the smaller defect the deviation was roughly 50%.

Running the sputtering equipment under normal operation condition, no defects greater than 20 µm in diameter could be found in the coatings. No flaking happened until the venting of the main chamber within the life time of the targets. The most critical material was found to by the silica. After installing new targets the defect densities were on elevated levels and dropped very fast to low levels were no defects grater than 10 µm were found. The defect densities of the 2 groups with smaller defects dropped to values below 50 cm^{-2} and stayed constant during a longer period. The duration of this period strongly depended on the surface roughness of all parasitic coated parts of the machine. After this period the defect levels increased until the end of the live time of the target and defects in class 10-20 µm occurred.

Changing from mid frequency powered dual magnetrons with metallic targets to radio frequency powered silica targets strongly improved the defect levels and the time behavior. The initial drop of defect densities was found to be the same, but the defect level improved constantly during the life time of the target. At the end only defects in the class 2-5 µm could be found. The defect level achieved values below 5 cm^{-2}.

Layers produced with RF-sputtering of silica were investigated regarding there LIDT @ 1064 nm (S on 1 according to ISO 11254-2, 12 ns pulse length, 1/e^2 beam diameter of 318 µm). The films were deposited on standard polished suprasil substrates. For a 4L thick single layer of silica the first observed damages occurred above 50 J/cm^2 and no decrease with the number of pulses was found. The 50%-LIDT H_{1on1} was determined to be above 100 J/cm^2 (Figure 4). Depositing an HR mirror (HL^11L) the first observed damages occurred at 60 -70 J/cm^2 and again no decrease with the number of pulses could be seen. The 50%-LIDT H_{1on1} was determined to be above 180 J/cm^2 (Figure 5).

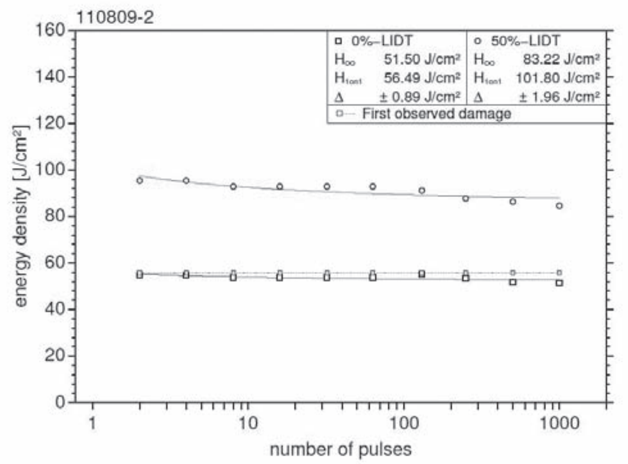

Figure 4: LIDT @ 1064nm of a single layer SiO_2, type 4L, standard polished suprasil substrate.

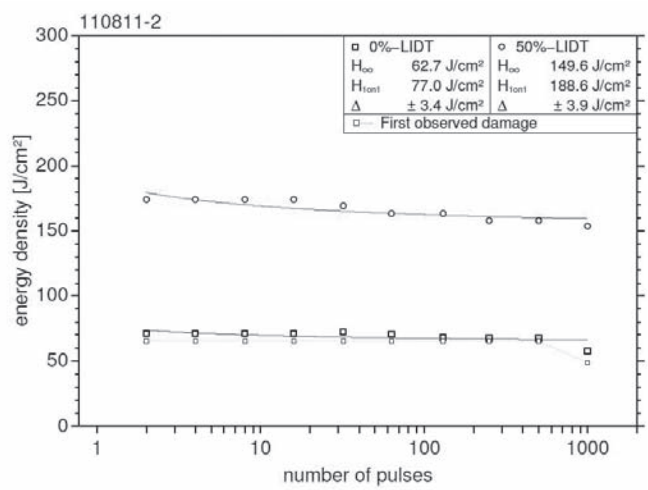

Figure 5: LIDT @ 1064nm of a HR mirror SiO_2/Ta_2O_5, type $(HL)^{11}$ L, standard polished suprasil substrate.

The same mirror deposited with mid frequency process for silica showed different behavior. The first observed damages at low number of pulses were above 35 J/cm^2 and decreased to a value of 13 J/cm^2. To see the influence of the substrate, a HR mirror ($HL^{18}L$) was deposited on a silicon wafer. The first observed damages increased to remarkable values above 150 J/cm^2 and the 50%-LIDT H_{1on1} was determined to be above 210 J/cm^2 (Figure 6).

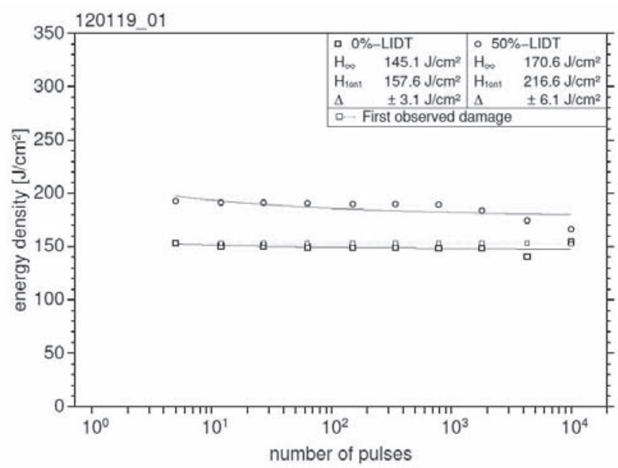

Figure 6: LIDT @ 1064nm of a HR mirror SiO_2/Ta_2O_5, type $(HL)^{18}$ L, silicon wafer substrate.

CONCLUSIONS

Plasma assisted reactive magnetron sputtering has shown in past 10 years remarkable results to produce demanding interference filters from the UV to the NIR spectral region. In combination with a highly accurate optical monitoring system thick layer stacks with high number of layers can be controlled automatically. High laser damage threshold can be achieved. By using radio frequency powered silica targets the defect density in the coating could be reduced by factor of 10 against the use of bipolar sputtering with mid frequency from metallic target. The use of radio frequency sputtering increased the LIDT at 1064 nm remarkable.

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