Controlled Plasma Assist for Precision Optical Coatings

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E-Gun Evaporation is still the most widely used technology to deposit dielectric thin films in precision optics. In order to increase the mass density of such layers ion beam or plasma beam assisted deposition is applied. This paper describes a new way of controlled plasma beam assist by using an ion energy controlled inductively coupled RF-Plasma Beam Source called "COPRA". The COPRA Plasma Assist enables the deposition of nearly ideal oxides or nitrides having the right atomic stoichiometry and mass density to be thermodynamically stable

In the field of precision optics there is an ongoing and increasing demand to improve the material properties like refractive index, optical transmission and thermal stability of dielectric thin films. The goal is to deposit metal oxides or nitrides having the right stoichiometry and mass density as thermodynamically required. Thermodynamically stable oxides or nitrides exhibit a minimum amount of structural defects and therefore a minimum value of absorption. Macroscopically such oxides or nitrides do not show any tensile or compressive stress values and will lead therefore, used in optical interference stacks, to drift free spectral properties. In order to deposit such high quality oxides and nitrides by using ion beam or plasma beam assisted e-gun evaporation certain specification of the ion or plasma beam are required:

- *The ion beam should contain only oxygen or nitrogen ions, ideally only atomic oxygen or nitrogen ions.*
- *The ion energy should be above the surface binding energy but below the bulk displacement energy.*
- *The independent control of ion energy and ion current density is required i.e. there is a need to increase the ion current density by keeping the ion energy constant.*

Only if these criteria are fulfilled the formation of stable oxides and nitrides are possible in a best way which is explained by the growth mechanism of the oxide layer itself. Providing atomic oxygen leads to the formation of the metal oxide without any activation energy which is needed in the case of molecular oxygen for dissociation.

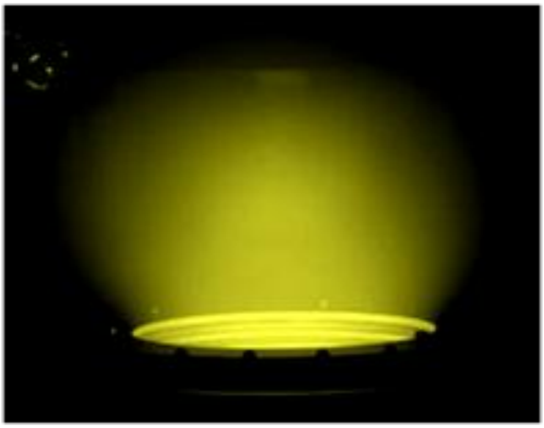

Figure 1: Atomic Copra Plasma Beam

Concerning the kinetic energy of the atomic oxygen ions it is important to note that if the kinetic is higher than the bulk displacement energy, the ions can penetrate the surface and are able to displace atoms in the bulk structure of the oxide layer which finally leads to a defect which acts as an absorption side in the optical layer. The last criteria of the independent control of ion energy and ion current density is required to govern the deposition process of such ideal oxides in order to run consistent long term stable defect-free industrial processes. Due to the fact that the deposition rate of the metal by e-gun evaporation can vary by the set of experimental conditions used in production there is a need to adjust the ion current density of the atomic oxygen beam in order to achieve a sufficient amount of kinetic oxygen to reach the required stoichiometry of the oxide. In order to keep the right ion energy to avoid the formation of bulk defects it is therefore necessary to vary the ion current density by keeping the ion energy constant.

Most of the conventional ion or plasma source technologies are not able to fulfill the above mentioned criteria. In the case of ion sources wherein the ions are accelerated by electrical dc-fields the operation with pure oxygen is not allowed and noble gases like Argon are required. Argon ions can be used to dense the growing oxides but Argon ions are not contributing to the film growth itself and have to transfer their kinetic energy to the film forming atoms by momentum transfer. This is due to the mass difference between the colliding argon atom and the film forming atom always related to the deposition of excess energy which leads to the formation of structural defects. Using Radio Frequency "RF" ion acceleration is therefore an improvement for the e-gun assist because it can operate with pure oxygen. Nevertheless most of the commercial available RF-Plasma Sources are still not able to offer the independent control of ion energy and ion current density and cannot deliver a sufficient amount of atomic oxygen ions because of their capacitive nature of plasma excitation.

All above mentioned criteria for the deposition of ideal oxides or nitrides are fulfilled by the COPRA Plasma Beam Technology. The COPRA is a 13.56 MHz RF-Plasma Source which is highly inductively coupled. Its main features are the independent control of ion energy and ion current density (figure 2a and 2b) in combination with a high dissociation degree of more than 90%, nicely demonstrated by the yellow optical emission color of atomic oxygen (figure 1). The ion energy itself of the atomic COPRA plasma beam can additionally be adjusted by adjusting the excitation RF voltage amplitude. This allows to adjust the ion energy continuously in the most suitable range for e-gun assist from 50 to 150eV (figure 3).

Using the COPRA plasma technology with these particular features makes the deposition of high precision optical coatings more efficient and easy. Placing the ion energy at a value at which the bulk defect generation is acceptable low, typically around 100eV or less, it is only required to adjust the ion current density by the RF-Power. Figure 4 shows the variation of the refractive index of Titanium Dioxide at a wavelength of 550nm as a function of the RF-power using COPRA Plasma Assist. The increase of the refractive index as a function of RF-power is explained by the increase of the ion current density as a function of RF-Power. By increasing the ion current density and by keeping the e-gun metal evaporation rate constant the mass density, monitored by the refractive index, will increase up to the thermodynamically required value for the particular stable oxide and will saturate at this value. Further increase of the ion current density will not lead to further densification of the Oxide, because the ion energy is kept below the bulk displacements energy.

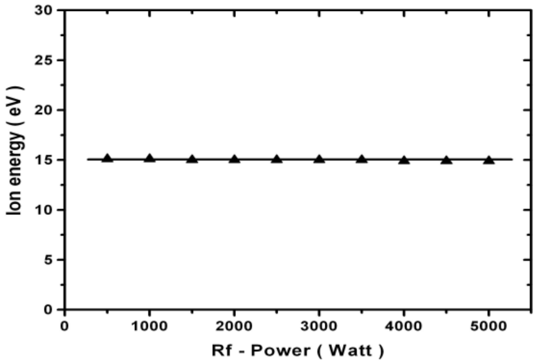

Figure 2a: COPRA ion energy variation as a function of RF-Power

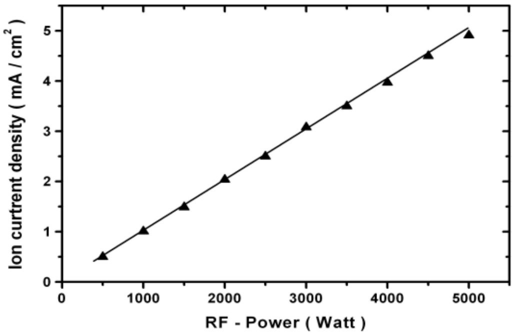

Figure 2b: COPRA ion current density variation as a function of RF-Power.

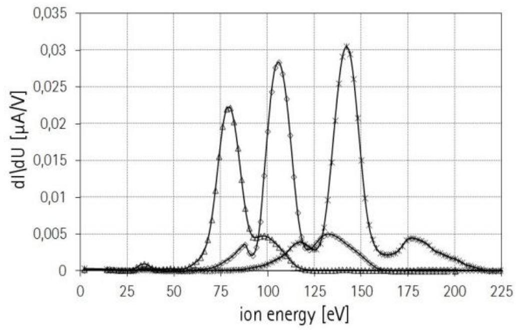

Figure 3: COPRA ion energy distribution variation

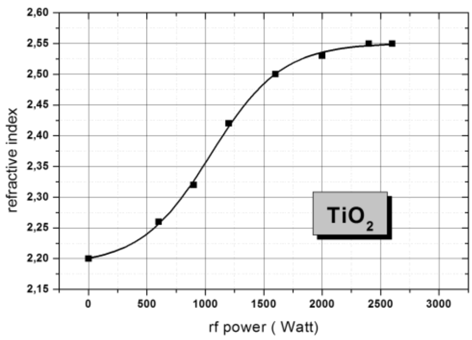

Figure 4: Refractive index variation of Titanium Oxides as a function of RF- Power.

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One more important feature of the COPRA plasma source technology is the ease of technical scaling (www.ccrtechnology.de) in the sense of up and down scaling of size and RF power. Independent of which particular design is used for the e-gun assist above mentioned criteria are always fulfilled and maximum degree of process transferability is guaranteed. The most favorite technical design for the e-gun assist is the COPRA IS300 as shown in figure 5.

Figure 5: The COPRA IS300 in build source for controlled plasma beam assist during the deposition of precision optical coatings

The COPRA IS300 is an in build version of the COPRA plasma technology and is suitable for a retro fit in existing e-gun evaporation systems either as system controlled component or standalone version. The IS300 can be used to assist the e-gun deposition calotte diameter from 800 to 1200 mm. In the case of larger calotte sizes two or more COPRA Sources can operate simultaneously. The main specifications of the IS300 are shown in table 1.

Operation gas	Oxygen
Pressure Range	1E-4 to 5E-4 mbar
RF-Power	3000 Watt, 13.56 MHz
Power Coupling	Integrated ICP - Remote Match
Ion Energy	50 to 150eV, independently controlled
Ion Current Density	0.05 to 0.5mA / cm2 at 700mm distance
Integrated Ion Current	3 A

Table1: COPRA IS300 Specifications

The COPRA plasma technology has been proven for the industrial production of precision optical coatings. Table 2 shows a selection of deposited Oxides with the corresponding maximum refractive index. As expected the refractive index of a selected oxides like SiO_2, TiO_2, T_2O_5 and Al_2O_3 is equal or close to be equal to the thermodynamically required value.

Table 2: Refractive index of Oxides deposited with COPRA Assist

Oxide	Refractive Index
SiO_2	1,49@ 550nm
TiO_2	2.55@ 550nm
Ta_2O_5	2.19@ 550nm
Al_2O_3	1.77@ 500nm

The fact that the COPRA assist can produce, thermo-dynamically stable Oxides is verified by annealing experiments. Operating the COPRA plasma source in the saturation regime which means above the power level that is needed to achieve the thermodynamically required stable mass density the drifts of the spectral data becomes less than 0.03ppm /K. See figure 6 at the back side of this paper.

Finally the interested reader of this paper may raise the question on how the plasma beam properties i.e. ion energy and ion current density of the COPRA plasma technology can be controlled over a large substrate size area of up to 1200mm. This is an important question because a high degree of uniform deposition in sense of thickness and refractive index is mandatory required over the whole substrate area. Taking into account that the COPRA Plasma technology allows to operate in the ion energy regime where no structural defects can be formed and where the refractive index substrates as a function of RF - power it is evident that the uniformity level during deposition can be tuned by the RF-power itself. As long as the metal deposition uniformity is guaranteed it is just required to operate the COPRA plasma source at such an RF-power value at which at each point of the substrate area it is guaranteed that the COPRA provides enough atomic oxygen ions to form the required oxide. Using the COPRA plasma assist the optical film thickness can be tuned in a uniform way with a variation of less than 0.3%.

Summary

This paper describes a novel technique to assist E-Gun Evaporation for the deposition of dielectric thin films in precision optics. The COPRA plasma assist allows one to control independently the ion current density in a regime in which the ion energy is high enough to dense the Oxide but still too low for creating structural defects. In conclusion the COPRA plasma technology enables the deposition of thermodynamically stable drift free oxides. In particular the high amount of atomic species provided by the COPRA plasma i.e. atomic oxygen or nitrogen ions leads to a minimum amount of excess energy during the formation of the oxide or nitride layer and therefore to a low degree of substrate temperature incremental changes during deposition. This is an important feature for the deposition of optical thin film stacks on polymer like substrates.

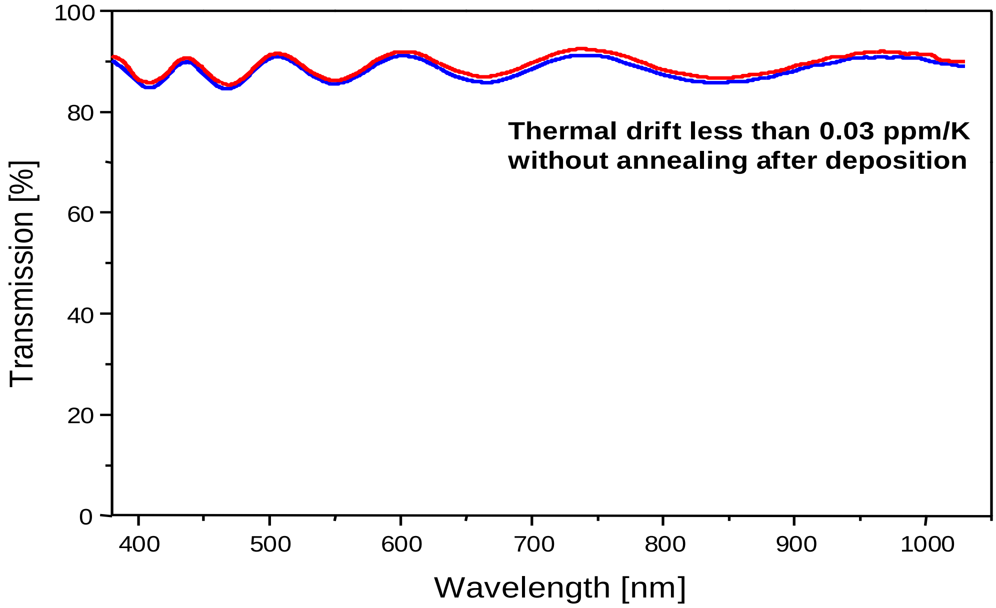

Figure 6: Spectral Data of a SiO2 layer as deposited and after thermal annealing

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The COPRA technology is patent protected!

US 6,936,144 B2