Coating Technology: Evaporation Vs Sputtering

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04.04.2016

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The aim of this document is to provide basic technical information regarding current AR coating technologies. Any information provided is not binding, can and will be changed without further notice. If you have questions, contact the owner of the document (Gianni.monaco@satisloh.com).

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INTRODUCTION

Coating by evaporation or by sputtering, also referred to as PVD (Physical Vapor Deposition) technologies, are nowadays the most widely used technologies for optical coatings. Applications are in the field of ophthalmic and precisions optics coatings, but PVD technologies are also applied for aesthetic, mechanical or electronic coatings and in many other areas that require thin film coating.

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1. Evaporation by means of electron beam

In thermal evaporation (or sublimation under vacuum) the bulk of the deposition material undergoes the transition from solid to vapor state by means of thermal heating or electron bombardment. The evaporated material is then carried to the substrate where the growing of the thin film occurs. The critical parameters of such a coating technology are mainly the average speed of the evaporated particles and their angular distribution. The base pressure must be kept in the high vacuum range to minimize the number of impact events between the evaporant particles and the residual gases in the chamber. High vacuum allows the particles to have a sufficiently "mean free path" for the thin film to grow at the substrate level. Coating by means of evaporation is usually carried out in a chamber as the one depicted in figure 1 below. The stainless steel chamber is evacuated with the help of a primary and a secondary pump (such as a turbo pump as in the example or a diffusion pump). The source of the evaporant is an e-beam gun head; the coating growth is controlled by a quartz crystal microbalance which can report both thickness and evaporation rate. An ion gun is added to increase the density of the coating material or to prepare the substrates for the deposition.

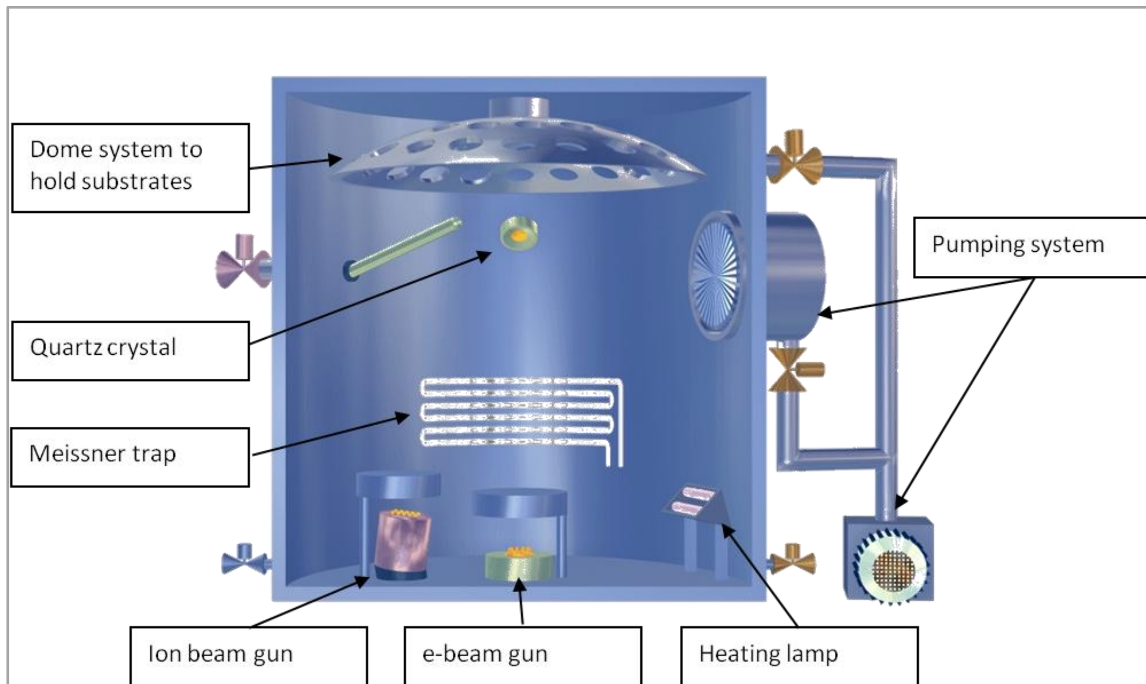

Figure 1: PVD evaporation chamber illustration

1.1 Distribution of the evaporant: uniformity mask

For a flat substrate, the distribution of the evaporated material is strongly dependent on the distance between the source and the substrate to be coated, as well as on the angle between the substrate and the evaporation source. The dependence is defined by the so-called cosine-law due to which the distance dependence is inversely proportional to the square of the distance and the angle dependence is proportional to the cosine of the angle. While the first can be mostly corrected by using a spherical calotte that holds the substrates, the second factor requires a uniformity mask to achieve uniform distribution of the evaporated material on all substrates.

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1.2 Coating materials with thermal or e-beam evaporation

Coating by means of material evaporation was a big step in coating technology when it was introduced in the 1930's. Today this technology allows using many different coating materials, as illustrated in the table below.

Deposition	Material	Typical Evaporant	Impurity	Deposition Rate	Temperature Range	Cost
Thermal	Metal or low melt-point materials	Au, Ag, Al, Cr, Sn, Sb, Ge, In, Mg, Ga CdS, PbS, CdSe, NaCl, KCl, AgCl, MgF_2, CaF_2, $PbCl_2$	High	1 ~ 20 A/s	~ 1800 °C	Low
E-Beam	Both metal and dielectrics	Everything above, plus: Ni, Pt, Ir, Rh, Ti, V, Zr, W, Ta, Mo Al2O3, SiO, SiO2, SnO2, TiO2, ZrO2	Low	10 ~ 100 A/s	~ 3000 °C	High

2. Sputter coating technology

Sputter coating, also known as "cathodic sputtering", is using the erosive action of accelerated ions at the surface of a target material. These ions have enough energy to remove (=sputter) particles at the target surface. In its simplest form, under high vacuum an electrical field is generated between an anode and a cathode plate (target) that is to be sputtered. By means of electrical voltage a working gas, generally Argon (Ar), is ionized generating a glow discharge. Since the target is kept at negative voltage, the positive Ar+ ions accelerate towards the target and "sputter" the atoms on its surface. In contrast to thermal evaporation, in sputtering the particles of the target are not displaced by heat, but by means of direct "momentum transfer" (inelastic collision) between the ions and the atoms of the material to be deposited. To accomplish sputtering a certain threshold energy is needed to remove atoms from the target surface and bring them into the vacuum. This is indicated by the sputtering efficiency S, which is the ratio of the sputtered material per Ar+ ion. Sputtering processes have much higher energy than evaporation processes which means that the sputtered material is usually in the form of ions with the ability to generate very dense coatings.

2.1 Magnetron sputtering

The most common sputtering technology is magnetron sputtering in which magnets are placed in the area of the target to keep the density of the sputtering ions very high which increases sputtering efficiency. That way it is possible to have a higher and more stable sputtering rate and consequently a faster deposition. The magnetron sputtering coating process does not require the microbalance control; online thickness control can be performed by sputtering time only: once started the coating deposition rate (i.e. thickness coated per second usually given as nm/s) depends on the magnetic field, the electric accelerating field and the gas pressure. If these parameters are constant, the deposition rate is stable as well and will be reproducible under the same conditions of the above mentioned parameters.

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The following figure 2 shows a circular silicon target under bombardment of Ar+ ions. It is possible to see the highest density of the ions (white light) which corresponds to the permanent magnetic field. However, sputtered atoms will come from the entire magnetron surface.

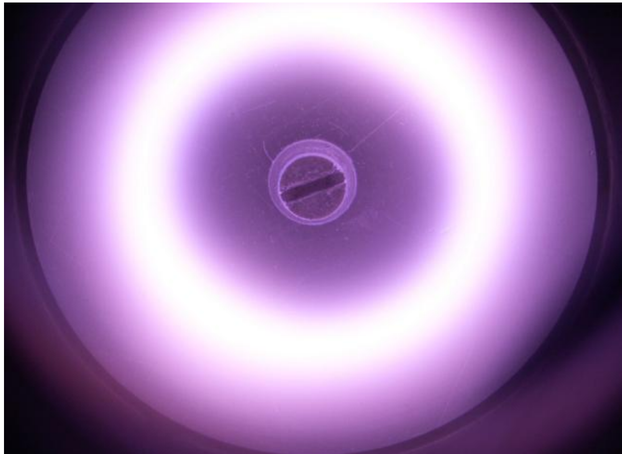

Figure 2: Plasma from a circular Silicon target under Argon ion bombardment

2.2 Reactive sputtering

In reactive magnetron sputtering, a reactive gas (or a gas mixture) is added to the inert gas (for example Argon) and reacts with the atoms eroded from the target during the layer formation on the substrate. The correct amount of reactive gas is determined by the required optical characteristics of the coated material. The film may be sub-stoichiometric, stoichiometric, or oxidized depending on the quantity of the reactive gases inserted into the coating chamber which leads to completely different physical and optical characteristics of the coated material1. With this technology, it is for example possible to coat high refractive index and low refractive index material layers using only one target.

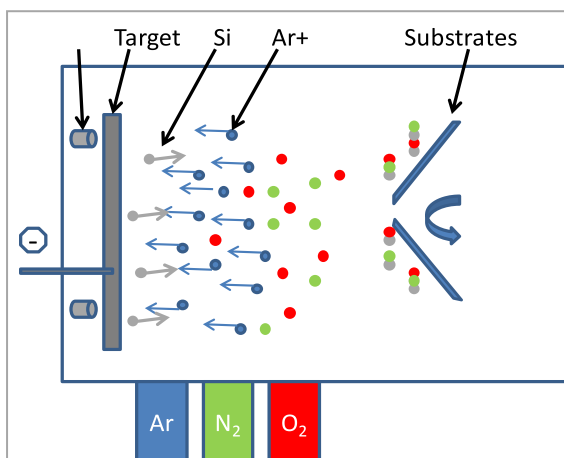

Figure 3: Reactive sputtering chamber illustration

Silicon is one of the most interesting coating materials. By mixing Silicon with Nitrogen it is possible to obtain the high refractive index material Si_3N_4 (n≅ 2.05 @520nm in its bulk form); by mixing it with oxygen it is possible to obtain the low refractive index material SiO_2 (n≅ 1.46 @520 nm in its bulk form). In figure 3, a schematic of the reactive sputtering technology is depicted. Nitrogen and Oxygen are used as reactive gases; Argon is used to create the plasma and sputter the Silicon target.

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3. Comparison between Evaporation and Sputter coating technologies

Sputtering is not an evaporation method. The high energy involved in the process will not create evaporated atoms as with thermal evaporation. Rather it creates a plasma of charged sputtered particles with much higher energy. Comparing the energy of the particles obtained by sputtering and by evaporation, the latter are much less energetic and therefore cannot organize themselves to have high density when growing a thin film on the substrate.

As illustrated in figure 1, e-beam evaporation needs the assistance of an ion beam during deposition to obtain higher density. This technology is referred to as Ion Assisted Deposition (IAD). In the ion beam gun a plasma of an inert or reactive gas is generated; the charged particles from the gun hit the growing film and increase film density. Higher density may enhance the mechanical properties of a coated film or increase the abrasion resistance of a coating. Another limitation of evaporation is its strong dependence on the evaporation rate of the evaporant material, which makes it impossible to evaporate substances with a complicated stoichiometry or even alloy materials. In contrast, Sputtering is much less sensitive to the target's stoichiometry. However, with sputtering it is impossible to coat fluoride materials (such as MgF_2) since the sputtered plasma destroys the structure of the fluoride films.

Looking to the ophthalmic industry, sputtering is now a mature technology for production of AR or Mirror coated lenses. Its key benefits are speed of process, deposition rate stability that allows to avoid the quartz crystal monitor and the possibility to carry out fully-automated processes.

The ability to automate is based on the following two facts:

1. Since sputtering uses a sputtering and/or a reactive gas, the sputtering process does not need the same low vacuum level as evaporation.

2. Distribution is not related to the evaporant cone as in the evaporation process. It is therefore possible to realize more compact coating chambers which can be integrated easier into an automated production line (along with a lens generator, polisher and a spin coater for hard coating).

Satisloh Sputtering machine

The above mentioned characteristics have led to the production of many in-line sputtering systems for various production applications in and outside of the ophthalmic industry. Today, as with evaporation, the combination of plastic substrate + hard lacquer + sputter AR coating can be tuned to achieve a high quality lens product with regards to optical, mechanical and durability properties.

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CONCLUSION

A very short overview of the most common PVD technologies has been provided. Thermal evaporation is the more mature technology: it has been in existence since the 1930's, skilled and trained operators are available all over the world and it allows coating almost all materials needed for "standard" coating applications (example: for coating ophthalmic lenses). Sputtering is a younger technology: it has been in existence since the early 1970's and has primarily been used for high end applications (such as space optics). However, today its benefits are also used for "standard" ophthalmic coatings. Thermal evaporation needs high vacuum while sputtering works at higher pressure, making it an easily automated technology to be deployed in in-line coating systems. The sputtering coating rate is highly tunable and - depending on the plasma generation technology - reaches very high and stable values with DC (=Direct Current) or pulsed DC technology. Both coating technologies can be tuned in order to obtain different physical properties of the coated films. The decision on which technology to use should be based on required production yield, costs, number of substrates to be coated, substrate type and the final characteristics of the coating.

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